Effects of low crude protein, amino acid fortified diets and neutral detergent fiber on finishing pig performance

by

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B.S., Universidad de la Frontera, 2001

B.S., Universidad Católica de Temuco, 2003

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

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Abstract

Eleven experiments using 5,434 growing-finishing pigs were performed in addition to the development of a model to predict dietary NE that yields the greatest economic benefit. Two experiments were conducted to determine the effect of dietary phytogenics on growth and carcass performance of growing-finishing pigs. The addition of the combination of two phytogenics products (EOM 1+2) to diets improved ADFI, HCW, and carcass ADG. However, there was no evidence for treatment differences for growth or carcass performance in a second study. Two experiments were conducted to determine the effects of feeding high SID Trp:Lys ratios with and without Ractopamine HCl (RAC) on growth and carcass characteristics of finishing pigs. In Exp. 1, whereas increasing SID Trp:Lys ratio above 20% improved growth and carcass performance when diets contained RAC, pigs fed SID Trp:Lys ratios above 20% in diets without RAC had reduced growth and carcass performance. Contrary in Exp. 2, pigs fed increasing SID Trp:Lys in diet containing RAC did not provide further performance benefits. Three experiments were conducted to determine the optimum dietary SID Lys and CP concentrations in finishing pigs over 100 kg. The SID Lys requirement to obtain 100% of maximum response was 0.55 to 0.63% depending on the response variable. Growth and carcass performance was maximized in diets containing at least 12% dietary CP. Four experiments were conducted to determine the effects of SBM concentration and whether dEB, choline, or K are the reasons that performance is reduced when pigs over 100 kg BW are fed low CP diets. Performance was reduced as SBM concentration was reduced in the diet. Choline, K, and dEB do not appear to be the reason that performance is reduced when SBM concentration is decreased in low CP diets fed to pigs over 100 kg BW. A Microsoft Excel®-based model to predict the value of dietary NE that yields the greatest economic return to the production system was

developed. Furthermore, a meta-analysis was conducted to incorporate the impact of NDF on carcass yield in the model.

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Table of Contents

List of Figures

List of Tables

Preface

This dissertation is original work completed by the author, J. A. Soto. All chapters were formatted for publication according to the required standards of the Journal of Animal Science. The appendix was formatted for publication according to the required standards of the Journal of Swine Health and Production.

Chapter 1 - Evaluation of dietary phytogenics on growth and carcass performance of growing-finishing pigs

ABSTRACT

Two experiments were conducted to determine the effect of dietary phytogenics on growth and carcass performance of growing-finishing pigs. In Exp. 1, 1,260 pigs (PIC 327 × 1050; initially 22.1 ± 1.3 kg) were used in a 125-d trial with 9 pens per treatment. There were 5 diets. Treatment 1 was the control diet with 6 dietary phases and no feed additives. Treatment 2 contained an essential oil mixture 1 (EOM 1) of caraway, garlic, thyme, and cinnamon fed in all phases with an inclusion rate of 0.015% in all phases. Treatment 3 contained EOM 1, fed from phase 3 to 6, and essential oil mixture 2 (EOM 2) of oregano, citrus, and anise fed in all phases with an inclusion rate of 0.015% and 0.0125% fed in all phases, respectively (EOM 1+2). Treatment 4 contained EOM 1 fed in all 6 phases. Treatment 5 contained 10 mg/kg of ractopamine HCl (RAC) with 16% CP in phase 6. In phase 6 diets, treatments 1 to 3 had 12% CP with treatments 4 and 5 at 16% CP. Overall (d 0 to 125), pigs fed diets with EOM 1+2 had greater ($P < 0.05$) ADFI compared with pigs fed the control and RAC diets. Similarly, pigs fed diets with EOM 1 in diets containing 12 and 16% CP had greater ($P < 0.05$) ADFI compared with pigs fed the RAC diet. However, pigs fed diets RAC had greater ($P < 0.05$) G:F compared with pigs fed the control and EOM 1 in diets containing 12 and 16% CP. For carcass characteristics, pigs fed EOM 1+2 had increased ($P < 0.05$) HCW and carcass ADG compared with pigs fed EOM 1 and 12% CP and the control diet. Similarly, pigs fed RAC had increased ($P < 0.05$) HCW and carcass ADG compared with pigs fed EOM 1 and 12% CP and the control diet. Furthermore, pigs fed RAC had the greatest ($P < 0.05$) carcass G:F and lean percentage

compared with the pigs fed the control diet and phytogenic treatments. To validate the responses, EOM 1 and 2 were fed in a 2 × 2 factorial with: 1) a control diet with no feed additives; 2) the control diet with 0.020% EOM 1; 3) the control diet with 0.0125% EOM 2, and 4) the control diet with the combination of 0.020% EOM1 and 0.0125% EOM2 (EOM 1+2). In Exp. 2, 317 pigs (DNA 241 × 600; initially 49.3 ± 2.1 kg) were used in a 87-d trial with 8 pens per treatment. For growth or carcass performance, there was no evidence for EOM 1 × EOM 2 interactions or treatment differences for ADG, ADFI, G:F, or for carcass traits. In summary, the addition of the combination of EOM 1+2 to the diets improved ADFI, HCW, and carcass ADG in Exp. 1, but these responses could not be validated in Exp. 2.

Key words: essential oils, feed additives, growing-finishing pig, phytogenics

INTRODUCTION

Phytogenic feed additives are plant-derived compounds added to animal feed to potentially improve animal health and performance. While the exact mode of action and physiological effects are not fully understood, most are associated with increasing diet palatability, enhancement of endogenous secretions, anti-oxidative activity, and antimicrobial effects (Windish et al., 2007).

Phytogenic substances evaluated in swine have been predominantly provided through essential oils. Essential oils are mixtures of secondary metabolites and may contain phenolic compounds, terpenes, lectins, aldehydes, polypeptides or polyacetylenes (Thacker, 2013). Use of essential oils in swine diets has received attention because in vitro studies show antimicrobial activity against harmful microflora commonly present in the pig gastrointestinal track (Michiels et al., 2009). While the mode of action has not been established, hydrophobic constituents

present in essential oils disintegrate the outer membrane of pathogenic bacteria (Lambert et al., 2001; Castillo et al., 2006; Windish et al., 2007). Positive results in swine have been reported associated to carvacrol and thymol, terpenes contained in oregano and thyme, respectively, which have demonstrated efficacy in vitro against several bacteria found in the intestinal tract (Burt, 2004). Improvements in animal performance have been reported with herbal or essential oil mixtures (Franz et al., 2009) and oregano (Zou et al., 2016); however, results have been inconsistent with Simitzis et al. (2010) or Ranucci et al. (2015) finding no benefits to a commercial plant extract containing oregano oil.

More research is needed to evaluate the effectiveness of phytogenics and to determine the greatest opportunities to obtain economic benefits. Therefore, the objective of these studies was to determine the effect of dietary phytogenics on growth and carcass performance of growing-finishing pigs.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. Experiment 1 was conducted at a commercial research-finishing site in southwest Minnesota. Experiment 2 was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS.

Experiment 1

A total of 1,260 pigs (PIC 327 × 1050, with initial and final BW of 22.1 ± 1.3 and 123.9 ± 3.1 kg, respectively) were used in a 125-d trial. Pens of pigs were weighed and randomly

assigned to dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 9 pens of 27 to 28 pigs per pen with each pen having a similar number of barrows and gilts per block. The facility was totally enclosed, environmentally controlled, and mechanically ventilated. Pens had completely slatted flooring and deep pits for manure storage. Each pen (3.05 × 5.49 m) was equipped with a 5-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and cup waterer for ad libitum access to feed and water. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens.

Pigs were fed a corn-soybean meal-dried distillers grains with solubles-based nutritional program with 6 dietary phases from 22 to 31, 31 to 57, 57 to 79, 79 to 97, 97 to 110, and 110 to 125 kg BW (Table 1.1 and 1.2). Treatment 1 was the control with no feed additives and contained 12% CP in phase 6 diet. Treatment 2 was the same formulation as treatment 1 but contained an essential oil mixture 1 (EOM 1; Digestarom; Biomin America, San Antonio, TX) of caraway, garlic, thyme, and cinnamon fed in all phases with an inclusion rate of 0.015%. Treatment 3 was the same diet formulation as treatment 1, but with 0.015% EOM 1 fed from phase 3 to 6 and 0.0125% essential oil mixture 2 (EOM 2; PEP 125; Biomin America, San Antonio, TX) of oregano, citrus, and anise fed in all phases (EOM 1+2). Treatment 4 contained 0.015% EOM 1 fed in all 6 phases with 16% CP in the phase 6 diet. Treatment 5 contained 10 mg/kg of ractopamine HCl (RAC; Paylean, Elanco Animal Health, Greenfield, IN) with 16% CP in the phase 6 diet.

Experiment 2

A total of 317 pigs (DNA 241 × 600, with initial and final BW of 49.3 ± 2.1 and 129.1 ± 2.7 kg, respectively) were used in an 87-d trial. Pens of pigs were weighed, and pens were randomly assigned to dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 8 pens of 9 to 10 pigs per pen with a similar number of barrows and gilts/treatments in each pen block. The facility was totally enclosed and environmentally regulated. Each pen (2.44 × 3.05 m) was equipped with a dry single-sided feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line and 1-cup waterer. Pens were located over a completely slatted concrete floor with a 1.20 m deep pit underneath for manure storage. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens.

Pigs were fed a corn-soybean meal-dried distillers grains with solubles-based nutritional program with four dietary phases from 49 to 63, 63 to 76, 76 to 103, and 103 to 129 kg BW (Table 1.3). Experimental treatments were arranged in a 2 × 2 factorial with: 1) a control diet with no feed additives; 2) the control diet with 0.020% essential oil mixture 1 (EOM 1) containing caraway, garlic, thyme, and cinnamon; 3) the control diet with 0.0125% essential oil mixture 2 (EOM 2) containing oregano, citrus, and anise, and 4) the control diet with the combination of 0.020% EOM1 and 0.0125% EOM2 (EOM 1+2). Per manufacturer recommendations, inclusion rate was increased to 0.020% for EOM 1 in Exp. 2 compared with 0.015% in Exp. 1.

Data collection

Pens of pigs were weighed and feed disappearance was measured on d 0, 13, 28, 47, 70, 90, 106, and 125 in Exp. 1 and on d 0, 14, 32, 59, and 87 in Exp. 2 to calculate ADG, feed disappearance, and G:F. In Exp. 1, the 3 heaviest pigs in each pen were weighed and sold according to standard farm procedures on d 106. Prior to marketing, the remaining pigs were individually tattooed with a pen ID number to allow for carcass measurements to be recorded on a pen basis. On d 125, final pen weights were taken, and pigs were transported to a USDA-inspected packing plant (JBS Swift and Company, Worthington, MN) for processing and carcass data collection. In Exp. 2, pigs were individually ear tagged with a unique RFID number to allow for carcass measurements to be recorded on a pig basis. On d 87, final pen weights and individual weights were taken, and pigs were transported to a commercial packing plant (Triumph, St. Joseph, MO) for processing and carcass collection. In Exp. 2, a considerable amount of RFID tags were dislodged and lost during the dehairing process. Thus, the recovery of carcass data from the processing plant was limited to 65, 66, 71, and 63% of the pigs for control, EOM1, EOM2, and EOM 1+2, respectively. In both experiments, carcass measurements taken at the plant included HCW, loin depth, backfat, and percentage lean. Percentage lean was calculated from plant proprietary equations and carcass yield was calculated by dividing the individual HCW at the plant by the pig pen average final live weight at the farm.

Diet Sampling and Analysis

In both experiments, diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of each dietary phase and stored at -20°C until analysis. Diet samples were submitted to Ward Laboratories, Inc. (Kearney, NE) and

Cumberland Valley Analytical Service (Hagerstown, MD) in Exp. 1 and 2, respectively. Diets were analyzed for DM (method 935.29; AOAC Int., 2012), CP (method 990.03; AOAC Int., 2012), ash (method 942.05; AOAC Int., 2012), ether extract (method 920.39 a; AOAC Int., 2012 for preparation and ANKOM XT20 Fat Analyzer [Ankom Technology, Fairport, NY], Ca, and P (method 968.08 b; AOAC Int., 2012 for preparation using ICAP 6500 [ThermoElectron Corp., Waltham, MA]).

Statistical Analysis

Data were analyzed using the PROC GLIMMIX procedure in SAS (SAS Institute, Inc., Cary, NC) with pen as the experimental unit and initial BW as a blocking factor. Dietary treatments were the fixed effect and block served as the random effect. Residual assumptions were checked using standard diagnostics on studentized residuals. The assumptions were reasonable met.

In Exp. 1, when treatment effects were established ($P < 0.05$), treatment least squares means were separated using the probability of differences (PDIFF). In Exp. 2, the main effects of EOM 1 and EOM 2 as well as their interaction were tested. In both experiments, HCW was used as a covariate for analyses of backfat thickness, loin depth, and percentage lean. Results were considered significant at $P < 0.05$ and a marginally significant $P > 0.05$ and $P \leq 0.10$.

RESULTS

The analyzed DM, CP, Ca, P, ether extract, and ash content of experimental diets for Exp. 1 (Table 1.4) and 2 (Table 1.5) were consistent with formulated estimates, except for EOM 1 diet in phases 1 and 2 of Exp. 1, which analyzed lower in CP than expected.

In Exp. 1, pigs fed diets with EOM 1+2 had greater ($P < 0.05$) ADFI compared with pigs fed the control and RAC diets (Table 1.6). Similarly, pigs fed diets with EOM 1 in diets containing 12 and 16% CP had greater ($P < 0.05$) ADFI compared with pigs fed the RAC diet. However, pigs fed diets RAC had greater ($P < 0.05$) G:F compared with pigs fed the control and EOM 1 in diets containing 12 and 16% CP.

For carcass characteristics, pigs fed EOM 1+2 had increased ($P < 0.05$) HCW and carcass ADG compared with pigs fed EOM 1 and 12% CP and the control diet. Similarly, pigs fed RAC had increased ($P < 0.05$) HCW and carcass ADG compared with pigs fed EOM 1 and 12% CP and the control diet. Furthermore, pigs fed RAC had the greatest ($P < 0.05$) carcass G:F and lean percentage compared with the pigs fed the control diet and phytogenic treatments. Additionally, pigs fed RAC had reduced ($P = 0.001$) backfat thickness compared with the pigs fed the control diet and the phytogenic treatments. Carcass yield also was improved ($P < 0.05$) in pigs fed RAC in comparison with pigs fed EOM 1 and 12% CP and the control diet.

In Exp. 2, there was no evidence for any EOM 1 × EOM 2 interactions for growth or carcass performance. For overall growth performance (d 0 to 87), there was no evidence for treatment differences for ADG, ADFI, or G:F (Table 1.7). Similarly, for carcass traits, there was no evidence for treatment differences in HCW, carcass yield, backfat, loin depth, or percentage lean.

DISCUSSION

Growth-promoting response to compounds of plant origin is highly variable in swine, with efficacy depending on factors such as type of essential oils, dosages, and purities (Namkung et al., 2004; Li et al., 2012; Bartos et al., 2016). Zou et al. (2016) studied the effects of diets

supplemented with 0.025% oregano essential oil on growth and carcass performance in finishing pigs, and observed improvement in ADG and G:F. The authors attributed the benefits to improvements in ADFI and speculated increased endogenous enzyme secretions. However, Simitzis et al. (2010), conducted a 35-d trial to evaluate the effects of diets with 0.025, 0.050, and 1.0% oregano oil on finishing pigs prior to slaughter, and found no differences on growth performance or carcass characteristics compared with pigs fed the control diet without phytogenics. The authors suggested that the lack of growth promoting effect was related to the high digestibility of the basal diet or excellent housing conditions leading to improved health status.

The increase of feed intake with pigs fed diets supplemented with EOM 1+2 in Exp. 1 is consistent with others whom have fed similar dietary phytogenics compounds (Allan and Bilkei, 2005; Kroismayr et al., 2006; Yan et al., 2010). Conversely, feed intake was not improved with phytogenic supplementation in Exp. 2. Phytogenic compounds can potentially increase feed intake by improving the palatability of diets resulting from the enhanced flavor and odor or by masking an unacceptable taste, thus maintaining desired organoleptic qualities in the diet (Nyachoti et al., 2004; Kroismayr et al., 2006; Franz et al., 2009). Nevertheless, the reported effects on feed intake are highly variable. Yan et al. (2011) conducted a 42-d trial to investigate the effect of diets supplemented with 0.025% and 0.050% of an herb extract mixture, including buckwheat, thyme, curcuma, black pepper, and ginger on growing pigs, and found ADFI improvements in pigs fed the herb mixture compared with pigs fed the control treatment without phytogenics. Conversely, Yan et al. (2010) conducted a 112-d experiment to evaluate the effect of diets containing 0.010% inclusion of an essential oil mix containing thyme, rosemary, oregano extract, and kaolin covered starch, on growth and carcass performance of growing-finishing pigs,

and found no improvements on growth performance. Similarly, Ranucci et al. (2015) conducted two 155-d experiments to evaluate the effect of diets containing 0.200% oregano oil and sweet chestnut wood on growth and carcass performance of growing-finishing pigs and found no improvements on growth performance in either experiments.

Essential oils have demonstrated antimicrobial effects, with high efficacy in vitro against several pathogens (Dusan et al., 2006; Michiels et al., 2009) suggesting that phytogenic compounds may be suitable to improve health and growth performance (Namkung et al., 2004). Bartos et al. (2016), conducted a 72-d trial to evaluate the effects of diets containing 0.010 and 0.015% inclusion of *Quillaja saponaria* and other plant extracts on growth performance of finishing pigs, and found that pigs fed diets containing the phytogenic had improved ADFI and ADG, without feed efficiency improvements, compared with the control group. Similarly, we observed improvements in ADFI in Exp. 1, however no impacts were observed on ADG or G:F in pigs fed diets supplemented with phytogenic compounds. Conversely, ADFI was not improved in pigs fed diets supplemented with phytogenics in Exp. 2.

Improvements in HCW and carcass growth in pigs fed diets supplemented with EOM 1+2 in Exp. 1, are consistent with results of others whom have fed oregano and caraway as main components to growing-finishing pigs (Zou et al., 2016; Bartos et al., 2016). Conversely, carcass performance was not improved in pigs fed diets supplemented with phytogenics in Exp. 2. Furthermore, Hanczakowska et al. (2015) conducted a 60-d experiment to evaluate the effect of 0.050% inclusion of an herbal extract mixture, containing sage, nettle, lemon balm and coneflower, on growing-finishing pig carcass performance and meat quality. Pigs fed diets supplemented with the herbal extract had no improvements in carcass performance or meat quality in agreement with the results of Yan et al. (2010) and Ranucci et al. (2015).

With the use of RAC in the U.S., the treatment structure of Exp. 1 included a group of pigs fed RAC to further evaluate replacement with phytogenic additives. For carcass performance, pigs fed diets with RAC had improved live and carcass feed efficiency, lean percentage, and reduced backfat. These results agree with typical responses to RAC in finishing pigs (Vezzoni de Almeida et al., 2012). Interestingly, pigs fed diet containing EOM 1+2 had similar ADG, HCW, and carcass ADG compared with pigs fed the diet containing RAC. This finding is the first we can determine that shows a phytogenic blend can potentially produce a similar growth effect to that of RAC fed pigs and needs further validation.

The variability in responses to phytogenics in swine may be due to several possibilities. According to Bartos et al. (2016) performance results of in vivo studies conducted with different phytogenics products are hardly comparable due to the high variability in composition, botanical origin, and processing of the essential oils and plant extracts. In our studies, a mixture of caraway, garlic, thyme, and cinnamon (EOM 1), and a mixture of oregano, citrus, and anise (EOM 2) were used. Essential oils of oregano and thyme, contains high amounts of the phenols carvacrol and thymol, which have demonstrated high efficacy as antimicrobial and antioxidants (Dusan et al., 2006). Supplementing diets with either oregano or thyme alone or in combination with other plant extracts in growing-finishing pigs has yielded inconsistent results; with beneficial results (Yan et al., 2010; Zou et al., 2016) and no responses to phytogenic interventions observed in others (Simitzis et al., 2010; Yan et al., 2010; Ranucci et al., 2015). Phytogenic dietary concentration has been suggested as another source of variability (Franz et al., 2009; Bartos et al., 2016). In Exp. 1, doses of 0.015 and 0.0125% were used for EOM 1 and EOM 2, respectively. By manufacturer recommendations, the inclusion rate of EOM 1 was increased to 0.020% in Exp. 2. Other studies, have used dilutions ranging from 0.010 to 1%, with

common inclusion of 0.025%. In addition, Simitzis et al. (2010) reported a numerical decrease in ADG and HCW of growing-finishing pigs when oregano oil was in concentrations above 0.050% of the diet.

There is conflicting data regarding phytogenic efficacy related to housing and environmental conditions. Several authors (Franz et al., 2009; Simitzis et al., 2010; Hanczakowska et al., 2015) have suggested that conditions conducive to supporting better health and reduced stress, as in a university environment, are less likely to observe favorable responses to phytogenic intervention. In our studies, Exp. 2 was conducted under university settings and like observations of Franz et al. (2009), Simitzis et al. (2010), and Hanczakowska et al. (2015), we observed no response to phytogenics. However, Exp. 1 was conducted under commercial conditions where we observed the greatest response to phytogenics. To support the differences in response to phytogenics based on environment, pigs in Exp. 2 had approximately 0.50 kg/d greater feed intake than those in Exp. 1. In contrast to this hypothesis, some studies have observed responsiveness to phytogenics under high health and controlled experimental conditions (Yan et al., 2011; Bartos et al., 2016; Zou et al., 2016). Further research is necessary to confirm if housing conditions impact the response to phytogenics.

In summary, the results of our experiments are inconsistent. In Exp. 1, pigs fed diets with EOM 1+2 had improved ADFI, HCW, and carcass ADG compared with pigs fed the control diet. In Exp. 2, the inclusion of these phytogenic feed additives did not provide any benefits in growth or carcass performance. Responses to feeding phytogenic additives have not been consistent among research studies. Consequently, more research is needed to confirm the beneficial effects on pig performance before these products are included in swine diets. In addition, there is still a need for a systematic approach to explain the efficacy and mode of action for each of type and

dose of active compound, as well as improving our understanding of potential interactions with other feed ingredients.

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TABLES

Table 1.1. Diet composition in Exp. 1 (as-fed basis)[1,2]

Item	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Ingredient, %					
Corn	59.36	65.13	70.50	74.05	76.42
Soybean meal, (46.5% CP)	23.13	17.48	12.24	8.85	6.44
DDGS[3]	15.00	15.00	15.00	15.00	15.00
Limestone	1.10	1.10	1.05	1.00	1.00
Monocalcium P, (21% P)	0.25	0.15	0.10	0.05	0.05
Salt	0.35	0.35	0.35	0.35	0.35
L-Lys-HCl	0.41	0.41	0.41	0.42	0.42
DL-Met	0.09	0.06	0.04	0.02	0.02
L-Thr	0.10	0.10	0.09	0.09	0.09
L-Trp	0.03	0.04	0.04	0.04	0.04
Phytase[4]	0.02	0.02	0.02	0.02	0.02
Trace mineral premix[5]	0.10	0.10	0.10	0.06	0.10
Vitamin premix[6]	0.08	0.08	0.08	0.06	0.06
Total	100.0	100.0	100.0	100.0	100.0
Calculated analysis					
Standardized ileal digestible (SID) AA, %					
Lys	1.12	0.98	0.85	0.77	0.71
Ile:Lys	61	60	58	57	56
Leu:Lys	139	145	152	157	162
Met:Lys	32	32	31	30	30
Met and Cys:Lys	56	56	56	56	57
Thr:Lys	62	62	62	62	63
Trp:Lys	19	19	18	19	18
Val:Lys	67	67	67	67	67
SID Lys: ME, g/Mcal	3.38	2.95	2.55	2.31	2.13
ME, kcal/kg	3,314	3.322	3,331	3,340	3,340
CP, %	19.7	17.4	15.3	14.0	13.0
Ca, %	0.57	0.53	0.49	0.45	0.44
P, %	0.46	0.42	0.38	0.36	0.35
Available P, %	0.30	0.28	0.26	0.24	0.24
Standardized digestible P, %	0.34	0.31	0.29	0.27	0.26

[1]Phase 1, 2, 3, 4, and 5 diets were fed from 22 to 31, 31 to 57, 57 to 79, 79 to 97, and 97 to 110 kg BW, respectively.

[2]EOM 1 was included at 0.015% in all phases only for treatments 2 and 4. EOM 1 was included at 0.015% from Phase 3 to 5 and EOM 2 was included at 0.0125% from Phase 1 to 5 only for treatment 3.

[3]Dried distillers grains with solubles (Valero Renewables, Aurora, MN).

[4]Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 301 FTU per kg of diet.

[5]Provided per kg of premix: Zinc 11 g from zinc oxide, Iron 11 g from iron sulfate, Manganese 3 g from manganese oxide, Copper 1,7 g from copper sulfate, Iodine 0.33 g ethylenediamine dihydroiodide, and Selenium 0.3 g from sodium selenite.

[6]Provided per kg of premix: Vitamin A 7,054,720 IU, Vitamin D3 1,102,300 IU, Vitamin E 35,274 IU, Vitamin B12 26 mg, Riboflavin (B2) 6,173 mg, Niacin 39,683 mg, d-Pantothenic acid 22,046 mg, Menadione 3,527 mg per kg.

Table 1.2. Phase 6 diet composition in Exp. 1 (as-fed basis)[1]

Item	Control	EOM 1	EOM 1+2	EOM 1	Ractopamine HCl
Ingredient, %					
Corn	85.50	85.48	85.47	76.13	76.10
Soybean meal, (46.5% CP)	12.38	12.38	12.38	21.66	21.66
Limestone	1.00	1.00	1.00	1.00	1.00
Monocalcium (21% P)	0.25	0.25	0.25	0.20	0.20
Salt	0.35	0.35	0.35	0.35	0.35
L-Lys-HCl	0.23	0.23	0.23	0.25	0.25
DL-Met	0.03	0.03	0.03	0.09	0.09
L-Thr	0.08	0.08	0.08	0.12	0.12
L-Trp	0.02	0.02	0.02	0.02	0.02
Ractopamine HCl[2]	0.00	0.00	0.00	0.00	0.05
Phytase[3]	0.02	0.02	0.02	0.02	0.02
Trace mineral premix[4]	0.10	0.10	0.10	0.10	0.10
Vitamin premix[5]	0.06	0.06	0.06	0.06	0.06
EOM 1[6]	---	0.02	0.02	0.02	---
EOM 2[7]	---	---	0.01	---	---
Total	100.0	100.0	100.0	100.0	100.0
Calculated analysis					
Standardized ileal digestible (SID) AA, %					
Lysine	0.65	0.65	0.65	0.90	0.90
Ile:Lys	63	63	63	63	63
Leu:Lys	155	155	155	137	137
Met:Lys	32	32	32	35	35
Met and Cys:Lys	60	60	60	60	60
Thr:Lys	67	67	67	67	67
Trp:Lys	19	19	19	19	19
Val:Lys	72	72	72	69	69
SID Lys:ME, g/Mcal	1.95	1.95	1.96	2.71	2.71
ME, kcal/kg	3,327	3,325	3,325	3,320	3,318
CP, %	12.2	12.2	12.2	16.0	16.0
Ca, %	0.49	0.49	0.49	0.51	0.51
P, %	0.36	0.36	0.36	0.39	0.39
Available P, %	0.23	0.23	0.23	0.23	0.23
Standardized digestible P, %	0.27	0.27	0.27	0.29	0.29

[1]Phase 6 diets were fed from 110 to 125 kg BW, respectively.

[2]Paylean (Elanco Animal Health, Greenfield, IN).

[3]Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 301 FTU per kg of diet.

[4]Provided per kg of premix: Zinc 11 g from zinc oxide, Iron 11 g from iron sulfate, Manganese 3 g from manganese oxide, Copper 1,7 g from copper sulfate, Iodine 0.33 g ethylenediamine dihydroiodide, and Selenium 0.30 g from sodium selenite.

[5]Provided per kg of premix: Vitamin A 7,054,720 IU, Vitamin D3 1,102,300 IU, Vitamin E 35,274 IU, Vitamin B12 26 mg, Riboflavin (B2) 6,173 mg, Niacin 39,683 mg, d-Pantothenic acid 22,046 mg, Menadione 3,527 mg per kg.

[6]EOM 1 was included at 0.015%.
[7]EOM 2 was included at 0.0125%.

Table 1.3. Diet composition from Phase 1 to 4 in Exp. 2 (as-fed basis)[1,2,3,4]

Item	Phase 1	Phase 2	Phase 3	Phase 4
Ingredient, %				
Corn	58.48	66.45	73.64	87.90
Soybean meal, (46.5% CP)	23.93	16.09	9.06	9.83
DDGS[3]	15.00	15.00	15.00	---
Monocalcium P, (21% P)	0.25	0.20	0.15	0.35
Limestone	1.08	1.05	1.00	1.00
Salt	0.35	0.35	0.35	0.35
L-Lys-HCl	0.41	0.42	0.44	0.29
DL-Met	0.08	0.05	0.02	0.02
L-Thr	0.10	0.10	0.09	0.08
L-Trp	0.02	0.03	0.04	0.02
Trace mineral premix[5]	0.15	0.13	0.10	0.08
Vitamin premix[6]	0.15	0.13	0.10	0.08
Phytase[7]	0.02	0.02	0.02	0.02
Total	100.0	100.0	100.0	100.0
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	1.14	0.96	0.80	0.65
Ile:Lys	62	60	58	60
Leu:Lys	146	154	164	161
Met:Lys	33	33	32	32
Met and Cys:Lys	58	58	58	62
Thr:Lys	62	62	62	65
Trp:Lys	18.7	18.7	18.8	18.2
Val:Lys	70	70	70	71
SID Lys: ME, g/Mcal	3.44	2.95	2.40	1.95
ME, kcal/kg	3,309	3,322	3,333	3,327
CP, %	20.9	17.8	15.0	12.3
Ca, %	0.56	0.51	0.46	0.48
P, %	0.47	0.42	0.38	0.37
Available P, %	0.28	0.26	0.24	0.22
Standardized digestible P, %	0.33	0.30	0.27	0.27

[1]Phase 1, 2, 3, and 4 diets were fed from 49 to 63, 63 to 76, 76 to 103, and 103 to 129 kg BW, respectively.

[2]EOM 1 was included at 0.020% of the diet at the expense of corn in all dietary phases.

[3]EOM 2 was included at 0.0125% of the diet at the expense of corn in all dietary phases.

[4]A combination of EOM 1 at 0.020% and EOM2 at 0.0125% of the diet were included at the expense of corn in all dietary phases.

[5]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.20 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.20 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[6]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[7]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 401 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 1.4. Chemical analysis of experimental diets in Exp. 1 (as-fed basis)[1]

	Item, %					
	DM	CP	Ca	P	Ether extract	Ash
Phase 1, d 0 to 13						
Control[2]	89.6	21.2	0.66	0.47	2.9	4.0
EOM 1[3]	89.2	17.8	0.61	0.46	3.0	3.9
EOM 1+2	89.6	20.1	0.70	0.47	3.0	4.4
Phase 2, d 13 to 47						
Control	89.4	18.6	0.66	0.46	3.4	3.7
EOM 1	88.9	16.8	0.61	0.43	3.0	3.8
EOM 1+2	88.6	19.1	0.60	0.44	2.9	3.9
Phase 3, d 47 to 70						
Control	88.8	14.7	0.52	0.38	3.1	3.3
EOM 1	88.8	15.7	0.51	0.41	3.5	3.4
EOM 1+2	89.1	15.7	0.54	0.38	3.4	3.3
Phase 4, d 70 to 90						
Control	88.4	14.1	0.60	0.40	3.3	3.2
EOM 1	89.1	14.6	0.45	0.38	4.0	3.2
EOM 1+2	88.6	15.0	0.49	0.42	4.0	3.2
Phase 6, d 106 to 125						
Control	87.4	12.7	0.46	0.36	2.5	2.8
EOM 1 (12% CP)	87.4	11.7	0.55	0.34	2.5	2.7
EOM 1+2	87.0	11.9	0.48	0.32	2.8	2.9
EOM 1 (16% CP)	88.0	15.3	0.62	0.41	2.8	3.4
Ractopamine HCl	89.5	14.1	0.64	0.38	3.0	3.5

[1]Multiple diet samples were collected from each diet throughout the study, homogenized, and then subsampled for analysis (Ward Laboratories, Inc. Kearney, NE).

[2]Control treatment (T1) had the same formulation to the ractopamine HCL treatment (T5) until phase 5.

[3]EOM 1 was included at 0.015% in all 6 phases for treatments 2 and 4.

[4]EOM 1 was included at 0.015% for Phase 3 to 6 and EOM 2 was included at 0.0125% for Phase 1 to 6 for treatment 3.

Table 1.5. Chemical analysis of experimental diets in Exp. 2 (as-fed basis)[1]

	Item, %					
	DM	CP	Ca	P	Ether extract	Ash
Phase 1, d 0 to 14						
Control	87.0	20.8	0.70	0.50	2.8	4.7
EOM 1[2]	86.8	20.3	0.72	0.46	2.7	4.4
EOM 2[3]	86.7	20.0	0.63	0.48	3.3	3.7
EOM 1+2[4]	86.4	20.0	0.72	0.45	2.5	4.2
Phase 2, d 14 to 32						
Control	86.9	17.6	0.64	0.45	3.6	3.7
EOM 1	86.9	17.5	0.65	0.46	3.7	4.1
EOM 2	86.8	16.9	0.63	0.46	3.3	4.1
EOM 1+2	86.9	17.2	0.63	0.43	3.5	4.2
Phase 3, d 32 to 59						
Control	87.2	15.0	0.66	0.39	3.9	3.0
EOM 1	87.4	14.8	0.59	0.39	4.1	3.7
EOM 2	87.4	14.1	0.59	0.37	3.7	3.3
EOM 1+2	87.3	14.3	0.58	0.38	3.7	3.1
Phase 4, d 59 to 87						
Control	86.4	11.9	0.69	0.35	2.7	3.6
EOM 1	86.4	12.4	0.67	0.35	2.7	3.1
EOM 2	86.4	12.4	0.64	0.36	3.0	3.5
EOM 1+2	86.4	12.0	0.58	0.36	2.7	3.2

[1]Multiple diet samples were collected from each diet throughout the study, homogenized, and then subsampled for analysis Cumberland Valley Analytical Service (Hagerstown, MD).

[2]EOM 1 was included at 0.020% in all dietary phases.

[3]EOM 2 was included at 0.0125% in all dietary phases.

[4]A Combination of EOM 1 at 0.020% and EOM2 at 0.0125% were included in all dietary phases.

Table 1.6. The effects of dietary phytogenics on the growth and carcass characteristics of growing-finish pigs (Exp. 1)[1,2,3]

CP in Phase 6, %:	12			16			Probability, *P*<
Feed additive:	Control	EOM 1[4]	EOM 1+2[5]	EOM 1[4]	Ractopamine HCl[6]	SEM	Treatment
Live weight, kg							
d 0	22.1	22.2	22.1	22.1	22.1	0.46	0.998
d 125	122.7	124.6	124.6	123.9	123.9	1.08	0.611
d 0 to 125							
ADG, kg	0.81	0.83	0.83	0.82	0.83	0.006	0.215
ADFI, kg	2.19^{bc}	2.23^{ab}	2.27^{a}	2.23^{ab}	2.17^{c}	0.020	0.003
G:F	0.371^{ab}	0.372^{ab}	0.366^{b}	0.370^{b}	0.381^{a}	0.0036	0.046
Carcass characteristics							
HCW, kg	94.5^{b}	94.9^{b}	97.1^{a}	96.1^{ab}	97.3^{a}	0.61	0.001
Carcass yield, %	77.0^{bc}	76.1^{c}	77.9^{ab}	77.6^{ab}	78.6^{a}	0.53	0.021
Backfat,[7] mm	17.1^{a}	17.1^{a}	16.7^{a}	16.9^{a}	15.4^{b}	0.28	<0.001
Loin depth,[7] mm	69.7	69.3	68.2	69.4	68.9	0.91	0.819
Lean,[7] %	56.8^{b}	56.7^{b}	56.8^{b}	56.9^{b}	57.8^{a}	0.19	0.002
Carcass performance							
Carcass ADG, kg[8]	0.62^{c}	0.63^{bc}	0.65^{a}	0.64^{ab}	0.65^{a}	0.004	0.002
Carcass G:F[9]	0.287^{b}	0.283^{b}	0.286^{b}	0.286^{b}	0.299^{a}	0.0028	<0.001

[1]A total of 1,260 pigs (PIC 1050 × 327) were used with 28 pigs per pen and 9 replications per treatment.

[2]Treatment 1 was the control with 12% of CP in Phase 6 diet. Treatment 2 contained EOM 1 fed all phases with 12% of CP in Phase 6 diet. Treatment 3 was EOM 1 fed from Phase 3 to 6 and EOM 2 fed all phases with 12% CP in Phase 6. Treatment 4 contained EOM 1 fed all 6 phases with 16% CP in Phase 6. Treatment 5 contained ractopamine HCL (9 g/ton) with 16% CP in Phase 6 diet.

[3]abc Least squares means within a row without a common superscript differ ($P < 0.05$).

[4]EOM 1 (mixture of caraway, garlic, thyme, and cinnamon). Biomin-America, San Antonio, TX. Included at 0.015% in all 6 dietary phases.

[5]EOM 2 (mixture of oregano, citrus, and anise). Biomin-America, San Antonio, TX. Included at 0.0125% from dietary phase 1 to 6 in combination with EOM 1, included at 0.015% only from Phase 3 to 5.

[6]Paylean (Elanco Animal Health, Greenfield, IN).

[7]Adjusted using HCW as a covariate.

[8]Carcass average daily gain = overall ADG * carcass yield.

[9]Carcass G:F = overall average feed intake/carcass average daily gain.

Table 1.7. Evaluation of dietary phytogenics on the growth performance and carcass characteristics of growing-finishing pigs (Exp. 2)[1]

	Feed additive					Probability, *P*<		
Item	Control	EOM1[2]	EOM2[3]	EOM1+2[4]	SEM	E1×E2[5]	EOM1	EOM2
Live weight, kg								
d 0	49.3	49.3	49.3	49.3	0.80	0.888	0.832	0.943
d 87	129.4	128.4	129.7	129.1	1.01	0.817	0.242	0.524
D 0 to 87								
ADG, kg	0.91	0.91	0.92	0.91	0.007	0.908	0.466	0.532
ADFI, kg	2.83	2.78	2.82	2.84	0.034	0.333	0.572	0.415
G:F	0.322	0.327	0.325	0.321	0.0033	0.193	0.913	0.579
Carcass characteristics								
HCW, kg	101.0	99.8	101.0	101.3	0.83	0.239	0.465	0.224
Carcass yield, %	74.8	75.0	74.8	74.9	0.31	0.948	0.594	0.881
Backfat, mm.[6]	16.5	17.0	16.7	16.8	0.37	0.466	0.414	0.972
Loin depth, mm.[6]	63.7	63.3	63.6	64.6	0.49	0.186	0.504	0.235
Lean, %[6]	53.8	53.9	53.9	53.9	0.22	0.890	0.934	0.847

[1]A total of 317 pigs (DNA 600 × 241) were used in an 87-d experiment with 9 or 10 pigs per pen and 8 replications per treatment.

[2]EOM 1 (mixture of caraway, garlic, thyme, and cinnamon). Biomin-America, San Antonio, TX. Included at 0.020% of the diet in all dietary phases.

[3]EOM 2 (mixture of oregano, citrus, and anise). Biomin-America, San Antonio, TX. EOM 2 was included at 0.013% of the diet in all dietary phases.

[4]A combination of EOM 1 at 0.020% and EOM2 at 0.0125% of the diet were included in all dietary phases.

[5]Interaction between EOM 1 and EOM 2.

[6]Adjusted using HCW as a covariate.

Chapter 2 - Evaluation of high standardized ileal digestible tryptophan:lysine ratios with and without ractopamine HCl on growth and carcass performance of finishing pigs under commercial conditions

ABSTRACT

Two experiments were conducted to determine the effects of feeding high SID Trp:Lys ratios with and without Ractopamine HCl (RAC) on growth and carcass characteristics of finishing pigs. In Exp. 1, 1,101 pigs (PIC 327 × 1050, initially 99.3 ± 3.5 kg, mean ± SD) were used in a 30-d trial with 26 to 27 pigs per pen and 7 pens per treatment. Pens of pigs were randomly assigned to 1 of 6 dietary treatments arranged in a 2 × 3 factorial with main effects of RAC (0 or 10 mg/kg) and SID Trp:Lys (20, 24, and 28%). Diets with and without RAC were formulated to 0.90 and 0.66% SID Lys, respectively. Overall (d 0 to 30), RAC × SID Trp:Lys interactions were observed (linear, $P < 0.05$) where increasing SID Trp:Lys ratio in pigs fed RAC increased final BW, ADG, and G:F but decreased these criteria when pigs were fed diets without RAC. Similarly, RAC × SID Trp:Lys interactions were observed (linear, $P < 0.05$) for carcass criteria with improvements in carcass ADG, carcass G:F, and HCW observed when pigs were fed increasing SID Trp:Lys in diets containing RAC, but not without RAC. To determine the optimum SID Trp:Lys in diets containing RAC (Exp. 2) 935 pigs (PIC 337 × 1050, initially 107.6 ± 2.5 kg, mean ± SD) were used in a 22-d trial with 23 to 24 pigs per pen and 8 pens per treatment. Dietary treatments included 5 SID Trp:Lys ratios (20, 22, 24, 26, and 28%). All diets were formulated to 0.90 SID Lys and contained 10 mg/kg RAC. Overall, increasing SID Trp:Lys increased (linear, $P < 0.05$) ADFI and grams of SID Trp intake. Furthermore, ADFI was

approximately 20% higher across treatments which led to greater grams of SID Trp intake in Exp. 2 compared with Exp. 1. However, unlike Exp. 1, there was no evidence for treatment differences in ADG or G:F. For carcass characteristics, there was no evidence for treatment differences for HCW, carcass yield, backfat thickness, loin depth, lean, carcass ADG, or carcass G:F. In conclusion, increasing SID Trp:Lys ratio above 20% improved growth and carcass performance when diets contained RAC. However, when pigs had an overall greater ADFI and subsequent greater grams of SID Trp intake in Exp. 2, increasing Trp:Lys did not provide benefits in overall growth or carcass performance. Furthermore, pigs fed SID Trp:Lys ratios above 20% in diets without RAC had reduced growth and carcass performance.

Key words: amino acid, growth, finishing pigs, ractopamine HCl, tryptophan

INTRODUCTION

Tryptophan is generally considered the second or third limiting amino acid in corn soybean-meal-based diets fed to growing and finishing swine (Burgoon et al., 1992). Although considerable research has been conducted to determine the optimum Trp requirement for swine, there are important discrepancies among studies (Susenbeth, 2006). The NRC (2012) SID Trp:Lys ratio requirement estimate for pigs above 75 kg is 17.7% of Lys. Zhang et al. (2012) suggested an ideal SID Trp:Lys ratio ranged from 19.7 to 23.6% for growing pigs depending on the response variable. Goncalves et al. (2015) reported that increasing SID Trp:Lys ratio to 24.5% in diets containing ractopamine HCl fed to finishing pigs improved ADG by 70 and 33 g/d in comparison with ratios of 18 and 21%, respectively. The growth response resulted from differences in feed intake, with an increase of 96 and 62 g/d in pigs fed 24.5% Trp:Lys ratio compared with pigs fed ratios of 18 and 21%, respectively.

Ractopamine HCl (RAC) is a β-adrenergic agonist used as a feed additive that repartitions nutrients from fat deposition to increase protein synthesis, muscle protein accretion as well as carcass quality. Furthermore, pigs fed RAC exhibit increases in growth, slight reduction in feed intake, and efficiency of growth improvements (Apple et al., 2007; Vezzoni de Almeida et al., 2012).

Currently, there is limited research available to establish if there is any benefit of increasing the SID Trp:Lys ratio in finishing pigs. In addition, research is lacking on the effects of high SID Trp:Lys ratios in diets without RAC. Thus, the objectives of these studies was to determine the effects of feeding high SID Trp:Lys ratios with and without RAC on growth and carcass characteristics of finishing pigs under commercial conditions.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. Both experiments were conducted at a commercial research finishing complex in southwestern Minnesota. The barns were naturally ventilated and double-curtain sided. Pens had completely-slatted flooring and deep pits for manure storage. Each pen (5.5 × 3.0 m) was equipped with a 4-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer to allow ad libitum access to feed and water. Each barn was equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions and diets as specified. This system can feed each pen any of the individual diets or a blend of two diets.

Experiment 1

A total of 1,101 pigs (PIC 327 × 1050, with initial and final BW of 99.3 ± 3.5 and 126.7 ± 4.0 kg, respectively, mean ± SD) were used in a 30-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 6 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment had 7 pens of 26 to 27 pigs per pen (0.61 to 0.63 m^2/pig) and each pen contained a similar number of barrows and gilts within each block.

Dietary treatments were arranged in a 2 × 3 factorial with or without (0 vs 10 mg/kg) RAC (Paylean; Elanco Animal Health, Greenfield, IN) and three standardized ileal digestible (SID) Trp:Lys ratios (20, 24, or 28%). Diets with and without RAC were formulated to 0.90 and 0.66% SID Lys, respectively (Table 2.1). Prior to the trial, from 82 to 100 kg, pigs were fed a corn-soybean meal-dried distillers grains with solubles-based diet that contained 14.0% CP, 0.77 SID Lys, 20% SID Trp:Lys ratio, and 2,535 Kcal NE/kg.

Experiment 2

To determine the optimum SID Trp:Lys ratio in diets containing RAC, a total of 935 pigs (PIC 337 × 1050, with initial and final BW of 107.6 ± 2.5 and 132.4 ± 2.7 kg, respectively, mean ± SD) were used in a 22-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 5 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment had 8 pens of 23 to 24 pigs per pen (0.69 to 0.72 m^2/pig) and each pen contained a similar number of barrows and gilts in each block. The dietary treatments included 5 SID Trp:Lys ratios (20, 22, 24, 26, and 28%). All diets were formulated with 0.90% SID Lys and contained 10 mg/kg RAC (Table 2.1). Prior to the trial, from 98 to 107 kg, these pigs were fed a

corn-soybean meal-dried distillers grains with solubles-based diet that contained 13.0% CP, 0.70% SID Lys, 20% SID Trp:Lys ratio, and 2,535 Kcal NE/kg.

Data collection

Pens of pigs were weighed and feed disappearance was measured on d 0, 9, 16, 23, and 30 in Exp. 1 and on d 0, 9, and 22 in Exp. 2 to calculate ADG, ADFI, and G:F. In Exp. 1, on d 23, the 3 heaviest pigs in each pen were weighed and sold according to standard farm procedures. On d 30 and 22 for Exp. 1 and Exp. 2, respectively, final pen weights were taken, and pigs were transported to a USDA-inspected packing plant (JBS Swift and Company, Worthington, MN) for processing and carcass data collection. Prior to marketing, pigs were individually tattooed with a pen ID number to allow for carcass measurements to be recorded on a pen basis. In both experiments, carcass measurements taken at the plant included HCW, loin depth, and backfat thickness. Percentage lean was calculated from a plant proprietary equation and carcass yield was calculated by dividing the HCW for pigs in the pen by the average final live weight at the farm.

Diet Sampling and Analysis

One representative sample of corn and soybean meal were collected at the feed mill prior to diet manufacturing and analyzed in duplicate for total AA (except Trp; method 994.12; AOAC Int., 2012), Trp (method 13904:2005; ISO, 2005), and CP (method 990.03; AOAC Int., 2012) by Ajinomoto Heartland Inc. (Chicago, IL), and these values were used in diet formulation. Other nutrients and SID AA digestibility coefficient values used for diet formulation were obtained from NRC (2012).

In Exp. 1 and 2, diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of each experiment and stored at -20°C. Diet samples were submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM (method 935.29; AOAC Int., 2012), CP (method 990.03; AOAC Int., 2012), ash (method 942.05; AOAC Int., 2012), ether extract (method 920.39 a; AOAC Int., 2012 for preparation and ANKOM XT20 Fat Analyzer [Ankom Technology, Fairport, NY], Ca, and P (method 968.08 b; AOAC Int., 2012 for preparation using ICAP 6500 [ThermoElectron Corp., Waltham, MA]). Additionally, total AA and CP analysis (conducted with the same methods previously described) were conducted in duplicate on composite samples of each treatment by Ajinomoto Heartland Inc.

Statistical Analysis

In both experiments, data were analyzed using the PROC GLIMMIX procedure in SAS (SAS Institute, Inc., Cary, NC) with pen as the experimental unit and initial BW as a blocking factor. Dietary treatments were the fixed effect and block served as the random effect in the analysis. Residual assumptions were checked using standard diagnostics on studentized residuals. The assumptions were reasonably met.

Preplanned linear and quadratic orthogonal contrast were tested using coefficients for equally spaced treatments and used to determine the main effects of increasing SID Trp:Lys ratio. In Exp. 1, main effects of RAC and SID Trp:Lys as well as their interactions were tested. In both experiments, HCW was used as a covariate for analyses of backfat thickness, loin depth, and percentage lean. Results were considered significant at $P < 0.05$ and a marginally significant $P > 0.05$ and $P \leq 0.10$.

RESULTS

The analyzed nutrients and total AA contents of experimental diets for Exp. 1 (Table 2.2) and Exp. 2 (Tables 2.3) were reasonably consistent with formulated estimates. In Exp. 2, free Trp of experimental diets analyzed as expected except slightly lower than expectation in the 28% SID Trp:Lys diet.

In Exp. 1, RAC × SID Trp:Lys interactions were observed (linear, $P < 0.05$; Table 2.4) for final BW, ADG, and G:F where increasing SID Trp:Lys improved performance in pigs fed diets containing RAC; however, the opposite effect was observed when diets did not contain RAC. A significant RAC × SID Trp:Lys interaction was observed (linear, $P = 0.002$) for grams of SID Trp intake. In addition, a marginally significant RAC × SID Trp:Lys interaction was observed (quadratic, $P = 0.075$) for SID Trp g/kg of gain. These were the result of increasing SID Trp:Lys ratio from 20 to 24% increased SID Trp g/kg of gain and SID Trp g/d intake to a greater extent in pigs fed diets without RAC than when diets contained RAC. Pigs fed diets with RAC had decreased ($P = 0.003$) ADFI compared with pigs fed diets without. No differences in ADFI were observed in pigs fed diets with increasing SID Trp:Lys ratios with or without RAC.

For carcass traits, RAC × SID Trp:Lys interactions were observed (linear, $P < 0.05$) for carcass ADG, carcass G:F, and a marginally significant interaction (linear, $P = 0.057$) was observed for HCW. The interactions were the result of improvements in these criteria when pigs were fed increasing SID Trp:Lys ratio in diets containing RAC, but not when pigs were fed diets without RAC. Pigs fed diets with RAC had improved ($P < 0.05$) carcass yield, backfat thickness, loin depth, and percentage lean compared with pigs fed diets that did not contain RAC. In addition, carcass yield was marginally improved (linear, $P = 0.075$) in pigs fed increasing SID Trp:Lys ratio in diets containing RAC.

In Exp. 2, increasing SID Trp:Lys ratio increased (linear, $P < 0.05$; Table 2.5) ADFI, grams of SID Trp intake, and SID Trp g/kg of gain. There was no evidence for treatment differences for ADG or G:F. Unlike in Exp. 1, in Exp. 2, there was no evidence for treatment differences for HCW, carcass yield, backfat loin depth, lean, carcass ADG or carcass feed efficiency when pigs were fed increasing SID Trp:Lys ratio when the diets contained RAC.

DISCUSSION

Increasing dietary concentration of Trp elicits brain serotonin synthesis, which is thought to be important in modulation of behavior and feed intake (Adeola and Ball, 1992; Henry et al., 1996) and may also participate in the inhibition of the transmission of pain and response to stress (Lenard and Dunn, 2005). Whereas feeding Trp-deficient diets has been shown to decrease feed intake and growth rate in finishing pigs (Guzik et al., 2005; Kendall et al., 2007), feeding high Trp diets has shown no adverse effects (Adeola and Ball, 1992). Guzik et al. (2005) conducted a 38-d trial to estimate the Trp requirement of finishing pigs from 74 to 104 kg in diets containing 11.5, 15.3, 19.2, 23.0, and 26.9% SID Trp:Lys and reported maximum responses for ADG and G:F at 19.2 SID Trp:Lys. Similarly, Kendall et al. (2007) conducted a 27-d trial to estimate the Trp requirement of finishing barrows from 98 to 123 kg in diets containing 13, 15, 17, 19, and 21% SID Trp:Lys and reported maximum responses for ADG and G:F at 17% SID Trp:Lys. Furthermore, Goncalves et al. (2015) conducted a 21-d trial to estimate the Trp requirements of finishing gilts from 106 to 126 kg. Gilts were fed 6 incremental additions of L-Trp, equating to 14.5, 16.5, 18.0, 19.5, 21.0, 22.5, and 24.5% SID Trp:Lys in a corn-soybean meal-dried distillers grains with solubles based diets containing RAC, and reported that 23.5% SID Trp:Lys ratio provided the 100% of maximum response for ADG. Conversely, Nitikanchana (2013) reported

no effects on growth performance with increasing SID Trp:Lys from 15 to 21% in finishing pigs from 74 to 131 kg fed corn-soybean meal-dried distillers grains with solubles based diets containing RAC. Results of Exp. 1 are consistent with Goncalves et al. (2015) findings, whom observed a maximum growth response in finishing gilts fed RAC-containing diets with 24.5% SID Trp:Lys ratio. However, we observed detrimental performance effects when diets did not contain RAC, which resulted in a RAC × SID Trp:Lys interaction. Furthermore, these results are consistent with Guzik et al. (2005), where ADG and G:F were decreased linearly with increasing SID Trp:Lys over 19.2% in diets not containing RAC.

Improvements in growth performance and carcass characteristics in finishing pigs with the use of RAC have been consistently demonstrated (Apple et al., 2007). The β-adrenergic agonist RAC redirects nutrients to favor lean rather than fat deposition, improving growth and carcass traits of finishing pigs (Vezzoni de Almeida et al., 2012). In our studies, pigs fed diets with RAC had improved growth and carcass performance, which agree with typical responses (Apple et al., 2007; Vezzoni de Almeida et al., 2012).

The RAC × SID Trp:Lys interactions for in Exp. 1 may be explained by RAC increasing Trp requirement by the brain. According to Lenard and Dunn (2005), changes in concentrations of brain Trp, as a response to different stressors, may affect the synthesis of brain serotonin (5-HT) and increase brain tryptophan concentrations.

Lenard et al. (2003) suggested that stress-related elevations in brain tryptophan in mice can be modified by beta-adrenoreceptors, suggesting the activation of peripheral sympathetic beta-adrenergic receptors. Whereas beta-adrenoreceptor antagonist can prevent increases in brain Trp, beta-adrenoceptor agonist has shown increases in brain Trp (Lenard and Dunn, 2005). Because Trp is the precursor of 5-HT, Trp is needed to replenish depleted 5-HT stores. In

addition, a constant supply of Trp is also necessary for brain protein synthesis (Dunn, 1988; Lenard and Dunn, 2005).

It has been demonstrated that stressors such as temperature, stocking density, and regrouping can decrease growth performance with additive effects (Hyun et al., 1998), with concomitant low serotonin levels in the hippocampal region of the brain in stressed pigs as suggested by Adeola and Ball (1992). In addition, optimum Trp:Lys ratio is also greater for maintenance than for protein accretion (Fuller, 1994) in agreement with NRC (2012) that recommends an increase SID Trp:Lys as pigs become heavier. In our studies, we speculate that, in finishing pigs with restricted floor space (average floor space 0.62 and 0.70 m^2 in Exp. 1 and Exp. 2, respectively), stress-related elevations of Trp in brain and serotonin synthesis could have been stimulated by RAC, thus increasing the needs of dietary Trp. Conversely, when pigs were fed increasing SID Trp:Lys in diets without RAC, Trp needs were lower, and the higher supply of Trp may have created imbalances in concentration of neurotransmitters, typically found in a stress response, and as a result pigs may lose weight or gain more slowly, and convert less efficiently (Adeola and Ball, 1992). Furthermore, the SID Trp:Lys requirements in diets not containing RAC in our study are consistent with the findings of Guzik et al. (2005) whom estimated the optimal SID Trp:Lys at 19.2 for ADG and feed efficiency, and Zhang et al. (2012) with an estimated optimal SID Trp:Lys at 19.7 and 20.0% for ADG and feed efficiency, respectively, for finishing pigs fed diets without RAC.

Guzik et al. (2005) reported that carcass yield was linearly increased with increasing levels of Trp from 11.5 to 26.9% of the diet in finishing barrows from 74 to 104 kg fed corn-feather meal-based diets. Similarly, Nitikanchana et al. (2013), reported linear improvement in carcass yield with increasing SID Trp:Lys in diets containing 30% DDGS in finishing pigs from

71 to 125 kg. These results are consistent with our finding in Exp. 1, where carcass yield was marginally improved with increasing Trp in finishing pigs fed diets containing RAC. However, carcass yield was not changed with increasing Trp in Exp. 2.

Contrary to Exp. 1, pigs in Exp. 2 fed increasing SID Trp:Lys ratio and RAC increased ADFI, grams of SID Trp intake, and SID Trp g/kg gain, but there was no improvement in ADG or G:F. One potential reason for the difference in response between experiments may be related to ADFI, were pigs had ~20% greater feed intake across treatments in Exp. 2 compared with Exp. 1. Furthermore, the grams of SID Trp was 18% greater in pigs fed diets with 20% SID Trp:Lys in diets containing RAC in Exp. 2 compared with Exp. 1. We speculate that overall higher feed intake leading to greater grams of SID Trp intake in Exp. 2 may not have allowed for pigs to further improve growth performance in response to Trp:Lys ratio.

In conclusion, increasing SID Trp:Lys ratio above 20% improved growth and carcass performance when diets contained RAC. However, when pigs had an overall ~20% greater ADFI and subsequent greater grams of SID Trp intake in Exp. 2, increasing SID Trp:Lys did not provide benefits in overall growth or carcass performance. Furthermore, pigs fed SID Trp:Lys ratios above 20% in diets without RAC had reduced growth and carcass performance.

Further research is necessary to explain the mechanism underlying the RAC × SID Trp:Lys interaction and determine the causes for response inconsistencies when feeding high SID Trp:Lys ratios in diets containing RAC to finishing pigs.

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TABLES

Table 2.1. Diet composition in Exp. 1 and 2 (as-fed basis)[1,2,3]

Item	Ractopamine HCl[4], mg/kg	
	0	10
Ingredient, %		
Corn	84.99	74.87
Soybean meal (46.5% CP)	12.79	21.74
Choice white grease	---	1.10
Limestone	1.00	0.95
Monocalcium P (21% P)	0.33	0.25
Salt	0.35	0.35
L-Lys-HCl	0.23	0.25
DL-Met	0.05	0.11
L-Thr	0.08	0.12
L-Trp	0.02	0.03
L-Val	---	0.02
Ractopamine HCl	---	0.05
Phytase[5]	0.02	0.02
Trace mineral premix[6]	0.10	0.10
Vitamin premix[7]	0.06	0.06
Total	100.0	100.0
Calculated analysis		
Standardized ileal digestible (SID) AA, %		
Lys	0.66	0.90
Ile:Lys	63	63
Leu:Lys	154	136
Met:Lys	34	37
Met & Cys:Lys	62	62
Thr:Lys	67	67
Trp:Lys	20	20
Val:Lys	71	71
His:Lys	42	40
SID Lys: NE, g/Mcal	2.59	3.53
NE NRC, kcal/kg	2,551	2,551
CP, %	12.4	16.0
Ca, %	0.50	0.50
P, %	0.38	0.40
Available P, %	0.24	0.24
Standardized digestible P, %	0.29	0.29

[1]Diets were fed from d 0 to 30 and from d 0 to 22 in Exp. 1 and 2, respectively.

[2]In Exp. 1, crystalline L-Trp was added at 0.027, and 0.054%, and at 0.036 and 0.072% to the 0 and 10 mg/kg RAC diets, respectively at the expense of corn to provide SID Trp: Lys of 22 and 24%.

[3]In Exp. 2, crystalline L-Trp was added at 0.018, 0.036%, 0.054, and 0.072% to the 10 mg/kg RAC diet at the expense of corn to provide SID Trp:Lys of 22, 24, 26, and 28%, respectively.

[4]Paylean (Elanco Animal Health, Greenfield, IN)

[5]Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 301 FTU/ kg of diet.

[6]Provided per kg of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[7]Provided per kg of premix: Vitamin A 7,054,720 IU, Vitamin D3 1,102,300 IU, Vitamin E 35,274 IU, Vitamin B12 26 mg, Riboflavin (B2) 6,173 mg, Niacin 39,683 mg, d-Pantothenic acid 22,046 mg, Menadione 3,527 mg.

Table 2.2. Chemical analysis of experimental diets in Exp. 1 (as-fed basis)[1]

	Ractopamine HCl, mg/kg					
	0			10		
SID Trp:Lys, %	20	24	28	20	24	28
Proximate analysis, %						
DM	85.9	86.0	85.3	85.6	86.5	86.1
CP	12.5	12.1	12.4	15.2	15.6	15.7
Ca	0.58	0.52	0.60	0.70	0.70	0.71
P	0.35	0.36	0.38	0.39	0.39	0.38
Ether extract	3.4	3.5	3.2	4.1	4.3	4.2
Ash	3.2	2.9	3.3	3.6	3.7	3.6
Amino acids, %						
Lys	0.80	0.73	0.74	0.98	1.08	1.00
Ile	0.47	0.45	0.45	0.63	0.71	0.63
Leu	1.17	1.12	1.13	1.37	1.50	1.40
Met	0.22	0.23	0.24	0.32	0.32	0.34
Met & Cys	0.47	0.44	0.44	0.56	0.59	0.59
Thr	0.51	0.50	0.51	0.64	0.72	0.70
Trp	0.15	0.16	0.17	0.20	0.23	0.25
Val	0.59	0.55	0.55	0.72	0.79	0.72
His	0.32	0.30	0.30	0.38	0.41	0.40
Phe	0.64	0.61	0.61	0.76	0.84	0.82
Free Lys	0.23	0.21	0.22	0.26	0.26	0.20
Free Trp	0.03	0.05	0.06	0.05	0.07	0.08

[1]Diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of the trial and 3 d prior to the end of the trial and stored at -20°C, then amino acid analysis was conducted on composite samples by Ajinomoto Heartland, Inc. (Chicago, IL). Samples of the diets were also submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM, CP, Ca, P, ether extract, and ash.

Table 2.3. Chemical analysis of experimental diets in Exp. 2 (as-fed basis)[1]

	Standardized ileal digestible Trp:Lys, %				
Item, %	20	22	24	26	28
DM	86.6	86.6	86.7	86.6	86.6
CP	16.0	15.8	15.4	15.0	15.8
Ca	0.73	0.50	0.63	0.58	0.63
P	0.38	0.37	0.41	0.35	0.36
Ether extract	3.6	3.4	4.1	3.3	3.7
Ash	2.9	3.3	3.3	3.0	3.7
Amino acids					
Lys	0.96	0.96	0.95	0.94	0.91
Ile	0.69	0.69	0.67	0.69	0.66
Leu	1.41	1.41	1.40	1.43	1.39
Met	0.33	0.33	0.33	0.34	0.32
Met & Cys	0.60	0.60	0.60	0.61	0.59
Thr	0.68	0.66	0.66	0.67	0.64
Trp	0.19	0.19	0.21	0.21	0.20
Val	0.78	0.78	0.77	0.77	0.75
His	0.40	0.40	0.39	0.39	0.39
Phe	0.78	0.79	0.77	0.78	0.76
Free Trp	0.03	0.05	0.07	0.09	0.07

[1]Diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of the trial and 3 d prior to the end of the trial and stored at -20°C, then amino acid analysis was conducted on composite samples by Ajinomoto Heartland, Inc. (Chicago, IL). Samples of the diets were also submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM, CP, Ca, P, ether extract, and ash.

Table 2.4. The effects of feeding high standardized ileal digestible (SID) Trp:Lys ratio with or without ractopamine HCl on growth performance and carcass characteristics of finishing pigs (Exp. 1)[1]

	Ractopamine HCl[2], mg/kg							Probability, *P* <				
	0			10				RAC × Trp:Lys			Trp:Lys Linear	
SID Trp:Lys, %	20	24	28	20	24	28	SEM	Linear	Quadratic	RAC	No RAC	RAC
Live weight, kg												
d 0	99.2	99.3	99.3	99.3	99.3	99.3	1.44	0.900	0.951	0.900	0.881	0.977
d 30	125.1	124.1	123.3	128.0	130.2	129.3	1.25	0.030	0.155	<0.001	0.084	0.165
d 0 to 30												
ADG, kg	0.88	0.84	0.82	0.98	1.03	1.02	0.022	0.012	0.183	<0.001	0.030	0.141
ADFI, kg	2.51	2.44	2.48	2.38	2.36	2.42	0.034	0.351	0.814	0.003	0.556	0.462
G:F	0.351	0.343	0.331	0.412	0.438	0.422	0.0070	0.010	0.056	<0.001	0.015	0.196
SID Trp intake, g/d	3.3	3.9	4.6	4.3	5.1	6.1	0.07	0.002	0.761	<0.001	<0.001	<0.001
SID Trp, g/kg gain	3.8	4.6	5.6	4.4	4.9	6.0	0.09	0.172	0.075	<0.001	<0.001	<0.001
Carcass characteristics												
HCW, kg	90.6	90.2	89.5	93.3	95.0	94.9	0.97	0.057	0.499	<0.001	0.273	0.102
Carcass yield, %	72.4	72.7	72.6	72.9	73.0	73.4	0.20	0.490	0.293	0.001	0.399	0.075
Backfat[3], mm.	17.2	16.7	17.5	15.5	15.1	16.0	0.35	0.675	0.964	<0.001	0.452	0.184
Loin depth[3], mm.	60.0	60.6	60.9	63.4	62.3	65.1	0.89	0.640	0.197	<0.001	0.512	0.193
Lean[3], %	55.6	55.9	55.5	57.0	57.1	56.1	0.22	0.892	0.443	<0.001	0.724	0.5872
Carcass performance												
Carcass ADG[4], kg	0.64	0.61	0.60	0.72	0.75	0.75	0.016	0.009	0.233	<0.001	0.039	0.090
Carcass G:F[5]	0.255	0.250	0.241	0.301	0.320	0.310	0.005	0.005	0.071	<0.001	0.017	0.096

[1]A total of 1,101 pigs (PIC 1050 × 327) were used with 26 or 27 pigs per pen and 7 replications per treatment.

[2]Paylean (Elanco Animal Health, Greenfield, IN).

[3]Adjusted using HCW as a covariate.

[4]Carcass average daily gain = overall ADG × carcass yield.

[5]Carcass G:F = carcass average daily gain/overall average daily feed intake.

Table 2.5. The effects of feeding high standardized ileal digestible (SID) Trp:Lys ratio in diets containing ractopamine HCl on growth performance and carcass characteristics of finishing pigs (Exp. 2)[1]

	SID Trp:Lys, %						Probability, $P <$	
Item	20	22	24	26	28	SEM	Linear	Quadratic
Live weight, kg								
d 0	107.6	107.6	107.6	107.6	107.6	0.92	0.822	0.927
d 22	131.7	132.7	131.6	133.0	132.7	0.97	0.247	0.955
d 0 to 20								
ADG, kg	1.10	1.14	1.10	1.15	1.13	0.025	0.340	0.733
ADFI, kg	2.86	2.91	2.89	2.96	3.00	0.037	0.007	0.675
G:F	0.384	0.390	0.378	0.390	0.376	0.0068	0.449	0.499
SID Trp intake, g/d	5.1	5.8	6.3	6.9	7.6	0.08	<0.001	0.448
SID Trp g/kg gain	5.2	5.6	6.4	6.7	7.4	0.11	<0.001	0.495
Carcass characteristics								
HCW, kg	98.2	98.8	98.1	98.9	98.6	0.73	0.550	0.839
Carcass yield, %	74.5	74.4	74.6	74.4	74.3	0.21	0.451	0.671
Backfat[2], mm.	15.3	14.6	15.3	14.9	15.3	1.41	0.926	0.809
Loin depth[2], mm.	70.1	70.6	69.5	71.7	69.6	0.62	0.797	0.421
Lean[2], %	57.9	58.5	57.9	58.4	57.9	1.01	0.938	0.791
Carcass performance								
Carcass ADG[3], kg	0.82	0.84	0.82	0.86	0.84	0.019	0.391	0.683
Carcass G:F[4]	0.286	0.290	0.282	0.290	0.279	0.0053	0.392	0.489

[1]A total of 935 pigs (PIC 1050 × 337) were used with 23 or 24 pigs per pen and 8 replications per treatment. All diets contained 10 mg/kg ractopamine HCl (Paylean, Elanco Animal Health, Greenfield, IN).

[2]Adjusted using HCW as a covariate.

[3]Carcass average daily gain = overall ADG × carcass yield.

[4]Carcass G:F = carcass average daily gain/overall average daily feed intake.

Chapter 3 - Optimum dietary standardized ileal digestible lysine and crude protein concentration for growth and carcass performance in finishing pigs greater than 100 kg

ABSTRACT

Three experiments were conducted to determine the optimum dietary standardized ileal digestible (SID) Lys and CP concentrations in finishing pigs over 100 kg. In Exp. 1, 253 pigs (DNA 600 × 241, initially 102.0 kg BW) were used in a 23-d trial with 7 to 8 pigs per pen and 8 pens/treatment. Dietary treatments contained 4 SID Lys concentrations (0.45, 0.55, 0.65, and 0.75%). To formulate the experimental diets, a corn-soybean meal diet with 0.45% SID Lys was formulated without L-lysine HCl. Then, a 0.75% SID Lys, corn-soybean meal diet was formulated including 0.23% L-lysine HCl. The 0.45 and 0.75% SID Lys diets were blended to create the 0.55 and 0.65% SID Lys diets. Increasing SID Lys increased (quadratic, $P < 0.05$) ADG and ADFI with pigs fed 0.55% SID Lys having the greatest final BW. Marginal improvements in G:F (quadratic, $P = 0.058$) and carcass yield (linear, $P = 0.051$) and reduction in backfat (quadratic, $P = 0.074$) were also observed with increasing SID Lys. Carcass ADG increased (linear, $P = 0.014$) and carcass G:F was marginally improved (quadratic, $P = 0.063$) as SID Lys increased, with pigs fed 0.55% SID Lys having the greatest HCW. The quadratic polynomial model for ADG and G:F predicted maximum response at 0.62 and 0.63% SID Lys, respectively. The broken line linear model predicted no further improvement in G:F over 0.55% SID Lys. In Exp. 2, 224 pigs (PIC 327 × 1050, initially 109.4 kg BW) were used in a 20-d trial with 7 pigs per pen and 7 to 8 pens per treatment. Dietary treatments included 4 concentrations of CP (10, 11, 12 and 13%) that were formed by reducing the amount of crystalline Lys in a

corn-soybean meal diet. For overall growth performance (d 0 to 20), increasing CP increased (linear, $P < 0.05$) ADG, ADFI, and carcass ADG with the greatest response observed in pigs fed the diet with 12% CP. Increasing diet CP also improved (linear, $P < 0.05$) G:F, final BW, HCW, and carcass G:F. In Exp. 3, 238 pigs (DNA 600 × 241, initially 111.8 kg BW) were used in a 26-d trial with 7 to 8 pigs and 6 pens per treatment. Dietary treatments included 5 concentrations of CP (9, 10, 11, 12, and 13%). Increasing CP improved (quadratic, $P < 0.05$) ADG, G:F, carcass ADG, and carcass G:F with the greatest response observed in pigs fed 13% CP. Increasing CP marginally increased (quadratic, $P < 0.074$) HCW, with the greatest response observed in pigs fed 12% CP. In conclusion, the SID Lys requirement for pigs from 100-122 kg was 0.55 to 0.63% depending on the response criteria with performance maximized in both genotypes with diets containing 12 to 13% CP.

Key words: amino acid, crude protein, finishing pigs, growth, lysine requirements

INTRODUCTION

Economic and environmental concerns have forced the development of low protein, AA fortified diets that deliver performance equivalent to diets with intact protein sources. However, in some studies, low CP diets have led to poorer performance, particularly in heavy weight finishing pigs. Research has shown that decreasing dietary CP below 13% may compromise finishing pig growth and carcass performance (Tous et al., 2014; Soto et al., 2017). Conversely, other research has reported no performance effects of lowering CP in finishing pigs when AA ratios are met (Kerr et al., 2003; Ball et al., 2013) however minimum CP levels have been maintained to at least 12%. Continuous advancements in modern pig genetics have resulted in increased growth performance and protein accretion, which may change dietary nutrient

requirements (O'Connell et al., 2005). Therefore, defining the optimum dietary Lys to maximize lean growth and optimize feed cost in finishing pigs is critical (Wei and Zimmerman, 2001).

Although considerable research has been conducted to determine the optimum Lys requirement for swine, there are limited data reporting the Lys requirements at heavy market weights (Kendall et al., 2007). Considering the limitations of available research to establish the optimal standardized ileal digestible (SID) Lys and CP concentrations for finishing pig diets, the objective of these studies was to determine the optimum levels of dietary SID Lys and CP for growth and carcass performance of finishing pigs weighing greater than 100 kg BW.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. All experiments were conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The facility was totally enclosed and environmentally regulated. Each pen (2.44 × 3.05 m) was equipped with a dry single-sided feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line and 1-cup waterer. Pens were located over a completely slatted concrete floor with a 1.20 m deep pit underneath for manure storage. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens. Prior to the experimental diets pigs were fed a corn-soybean meal-based diet with 14.2% CP, 0.72% SID Lys, and 2,535 kcal/kg of NE in all experiments. Pigs were provided ad libitum access to water and to feed in meal form throughout the experiments.

Experiment 1

To determine the SID Lys requirements of finishing pigs, a total of 253 pigs (DNA 600 × 241), with initial and final BW of 102.0 ± 1.2 and 123.4 ± 2.2 kg, respectively, were used in a 23-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 4 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 8 pens of 7 to 8 pigs per pen with a similar number of barrows and gilts in each pen. The dietary treatments included 4 SID Lys concentrations (0.45, 0.55, 0.65, and 0.75%). To formulate the experimental diets, a corn-soybean meal diet with 0.45% SID Lys was formulated without L-Lys HCl. Then, a 0.75% SID Lys, corn-soybean meal diet was formulated including 0.23% L-Lys HCl and other feed-grade AA as necessary to maintain ratios relative to Lys. Ratios were maintained well above NRC (2012) requirement estimates to ensure that other AA were not limiting. The 0.45 and 0.75% SID Lys diets were blended to create the 0.55 and 0.65% SID Lys diets (Table 3.1).

Experiment 2

A total of 224 pigs (PIC 327 × 1050, with initial and final BW of 109.4 ± 1.8 and 126.8 ± 2.5 kg, respectively) were used in a 20-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 4 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 7 to 8 pens of 7 pigs per pen with 4 barrows and 3 gilts in each pen.

Dietary treatments included 4 CP concentrations (10, 11, 12, and 13%). To formulate the experimental diets, a 13% CP corn-soybean meal diet with 0.23% L-Lys HCl was formulated. Then L-Lys HCl was included at 0.52, 0.43, and 0.33% of the diet to reach the desired levels of

10, 11, and 12% CP, respectively (Table 3.2). Diets were isocaloric (NE = 2,443 kcal/kg) and formulated to 0.66% SID lysine. Other AA were added as necessary to maintain ratios at or above NRC (2012) requirements estimates relative to Lys.

Experiment 3

A total of 238 pigs (DNA 600 × 241), with initial and final BW of 111.8 ± 1.7 and 134.6 ± 2.1 kg, respectively, were used in a 26-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 5 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 6 pens of 7 to 8 pigs/pen with a similar number of barrows and gilts in each pen.

The dietary treatments included 5 concentrations of CP (9, 10, 11, 12, and 13%). To create the experimental diets, a 13% CP corn-soybean meal diet with 0.04% L-Lys HCl was formulated. Then, a 9% CP diet was formulated including 0.43% L-Lys HCl and other synthetic AA as necessary to maintain ratios relative to Lys. Ratios were maintained well above NRC (2012) requirement estimates to ensure that other AA were not limiting. The 9 and 13% CP diets were blended to create the 10, 11, and 12% CP diets (Table 3.3). Based on the results of Exp. 1, diets were formulated to 0.55% SID Lys, which was considered marginally deficient for optimal performance, and not underestimate the ratio of other AA to Lys. Diets were isocaloric (NE = 2,451 kcal/kg) which was achieved by adjusting the amount of added fat as corn and soybean meal amounts changed in the diet.

Data collection

Pens of pigs were weighed, and feed disappearance was measured weekly and at the end of each experiment to calculate ADG, feed disappearance, and G:F. Prior to marketing, pigs were individually tattooed with a unique ID number to allow for carcass measurements to be recorded on a pig basis in all experiments. At the end of each experiments (d 23, 20, and 26 for Exp. 1, 2, and 3, respectively) individual weights were taken, and pigs were transported to a USDA-inspected packing plants (Triumph St. Joseph, MO in Exp. 1 and 3; Farmland Crete, NE in Exp.2;) for processing and carcass data collection. In Exp. 1, carcass measurements only included HCW. In Exp. 2 and 3, carcass measurements included HCW, loin depth, backfat, and percentage lean. In all experiments, carcass yield was calculated by dividing the HCW at the plant by the final live weight at the farm.

Diet Sampling and Analysis

In all experiments, diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of each trial and stored at -20°C until analysis. Diet samples were submitted to Cumberland Valley Analytical Service (Hagerstown, MD) in Exp. 1 and 3, and Ward Laboratories, Inc. (Kearney, NE) in Exp. 2. Diets were analyzed for DM (method 935.29; AOAC Int., 2012), CP (method 990.03; AOAC Int., 2012), ash (method 942.05; AOAC Int., 2012), ether extract (method 920.39 a; AOAC Int., 2012 for preparation and ANKOM XT20 Fat Analyzer [Ankom Technology, Fairport, NY], Ca, and P (method 968.08 b; AOAC Int., 2012 for preparation using ICAP 6500 [ThermoElectron Corp., Waltham, MA]). Additionally, diet samples were submitted for total AA analysis (method 994.12; AOAC Int., 2012) from Exp. 1

and 3 and free Lys (method 994.13; AOAC Int., 2012) in Exp. 1 by Ajinomoto Heartland, Inc. (Chicago, IL).

Statistical Analysis

In all experiments, data were analyzed using the PROC GLIMMIX procedure in SAS (SAS Institute, Inc., Cary, NC) with pen as the experimental unit and initial BW as a blocking factor. Dietary treatments were the fixed effect and block served as the random effect in the analysis. Preplanned linear and quadratic orthogonal contrast were built using coefficients for equally spaced treatment and used to determine the main effects of increasing SID Lys in Exp. 1 and CP in Exp. 2 and 3. Hot carcass weight served as a covariate for the analysis of backfat, loin depth, and lean percentage. Heterogeneous residual variances as a function of treatment combinations were fitted as needed according to the procedures suggested by Gonçalves et al. (2016). Model assumptions were checked using studentized residuals and were considered to be appropriately met. In Exp. 1, PROC GLIMMIX and PROC NLMIXED were used to predict the SID Lys dose response curves to optimize ADG and G:F. Dose response models evaluated were quadratic (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models. Best fit was determined using Bayesian Information Criterion (BIC), with a lower number being indicative of an improved fit. A decrease in BIC greater than 2.0 among models for a response criterion was considered an improved fit. Results from all experiments were considered significant at $P < 0.05$ and a marginally significant $P > 0.05$ and $P \leq 0.10$.

RESULTS

The analyzed nutrient and total AA of diets in Exp. 1, 2, and 3 (Tables 3.4, 3.5, and 3.6, respectively) were reasonably consistent with formulated estimates.

Experiment 1

For overall growth performance (d 0 to 23), increasing SID Lys improved ADG and ADFI (quadratic, $P < 0.05$) with pigs fed 0.55% SID Lys having the greatest ADG and ADFI (Table 3.7). Increasing SID Lys increased (linear, $P < 0.05$) grams of SID Lys intake per kg of gain and SID Lys intake. In addition, marginal significant improvement (quadratic, $P < 0.10$) was observed in G:F with increasing SID Lys.

For carcass characteristics, a marginal significant increase in carcass yield (linear, $P = 0.051$) and decrease (quadratic, $P = 0.074$) in backfat was observed when increasing SID Lys. Carcass ADG increased (quadratic, $P = 0.014$) and carcass G:F was marginally improved (quadratic, $P = 0.063$), resulting in pigs fed 0.55% SID Lys having the greatest HCW.

The QP model for ADG resulted in the best fit predicting 95, 98, and 100% of maximum response at 0.50, 0.55, and 0.62% SID Lys, respectively (Figure 3.1). The QP model equation was: ADG, g = -350.1 + 4237.0 × (SID Lys, %) – 3414.0 × (SID Lys, %)^2. The QP and BLL models had a comparable fit for G:F (BIC = 278.2 vs 279.3, QP and BLL, respectively) with the QP model predicting 95, 98, and 100% of maximum feed efficiency at 0.48, 0.54, and 0.63% SID Lys, respectively. The QP model equation was: G:F = 71.9 + 809.6 × (SID Lys, %) – 639.2 × (SID Lys, %)^2. The BLL model predicted no further improvement in G:F over 0.55% SID Lys (95% CI: [0.43, 0.67]%). The BLL model equation was: G:F = 324.1 – 163.2 × (0.554 - SID Lys, %) if SID Lys < 0.554%, and 324.1 if SID Lys > 0.5544 (Figure 3.2).

Experiment 2

For overall growth performance (d 0 to 20), increasing dietary CP increased (linear, $P < 0.05$) ADG, ADFI, G:F, and grams of digestible CP per kg of gain, with the greatest response for pigs fed the diet containing 12% CP with only marginal improvements thereafter (Table 3.8). In addition, increasing CP also improved (linear, $P < 0.05$) G:F and final BW.

For carcass characteristics, increasing CP increased (linear, $P = 0.001$ and quadratic, $P = 0.070$) carcass ADG with the greatest response for pigs fed the diet with 12% CP. Furthermore, HCW increased (linear, $P = 0.040$) with increasing dietary CP without any influence on carcass yield. Similarly, carcass G:F improved (linear, $P = 0.050$) with increasing CP.

Experiment 3

For overall growth performance (d 0 to 26), increasing dietary CP improved (quadratic, $P < 0.001$) ADG and G:F with the greatest improvement as CP was increased from 9 to 11% with smaller improvements as CP was further increased to 13% (Table 3.9). Similarly, increasing CP marginally increased (linear, $P = 0.073$) ADFI with a large increase in ADFI as CP was increased from 9 to 10% with little change in ADFI thereafter. In addition, increasing CP improved (quadratic, $P = 0.001$) grams of digestible CP per kg of gain.

For carcass characteristics, increasing CP increased (quadratic, $P < 0.001$) carcass ADG and improved (quadratic, $P < 0.05$) carcass G:F with the greatest response for pigs fed the diet with 13% CP. Furthermore, increasing CP marginally increased (quadratic, $P = 0.074$) HCW, with the greatest response for pigs fed the diet with 12% CP. There was no evidence for treatment differences in carcass yield, backfat, loin depth or percentage lean.

DISCUSSION

Determining the dietary standardized ileal digestible lysine requirement estimates

Because essential AA requirements for finishing pigs are based on ratios to Lys, an accurate requirement estimate for Lys in the late-finishing period becomes crucial to maximize lean growth and optimize feed cost (Baker, 1997; Wei and Zimmerman, 2001). Continuous advancements in modern pig genetics have resulted in superior growth performance and protein accretion, potentially increasing dietary nutrient requirements (O'Connell et al., 2005). In addition, advanced dose-response models that account for correlated data structures and heterogeneous variances have provided the means for better requirements estimations (Gonçalves et al., 2016).

Early work to determine the Lys requirements of growing-finishing barrows and gilts conducted by Cromwell et al. (1993) suggested that the SID Lys requirement was 0.51 and 0.76 for barrows and gilts, respectively. Similarly, Hahn et al. (1995) suggested that the SID Lys requirement in late-finishing barrows and gilts weighing between 80 and 120 kg was 0.49 and 0.52%, respectively. Furthermore, in a review of literature, Kerr et al. (1993) estimated that the SID Lys requirements was 0.42, 0.51, and 0.62% for low, medium, and high lean growth genotypes, respectively. Dean (2005) reported that growth performance of 90-kg barrows was the highest when diets contained 0.525% SID Lys. Most recently, Goncalves et al. (2017) completed a meta-analysis with PIC genetics lines, and determined the SID Lys requirements are 0.70 and 0.75% for barrows and gilts over 100 kg BW, respectively. In our study, 100% of maximum response for ADG and G:F were achieved at 0.62 and 0.63% SID Lys, which is higher than previous reports (Hahn et al., 1995; Dean 2005), yet in line with the requirements suggested

by Kerr et al. (1993) for higher lean growth genotypes. However, our estimates are considerably lower than those of Goncalves et al. (2017).

According to Kendall et al. (2007), variation in Lys requirements could be attributable to differences in the genetic capacity for protein deposition and other factors, such immune stress and differences in AA digestibility within dietary ingredients. In our study, the highest levels of feed intake (3.01 and 2.85 kg/d) were achieved with pigs consuming diet containing 0.55 and 0.65% SID Lys, resulting in a 16.6 and 18.5 g/d SID Lys intake, respectively. Conversely, Goncalves et al. (2017) reported that 100-135 kg BW barrows and gilts had an average feed intake of 2.83 and 2.61 kg/d of diets containing 0.70 and 0.75% SID Lys, resulting in SID Lys intake of 19.5 and 19.7 g/d, respectively.

According to Goncalves et al. (2017) higher g/d of Lys required could be attributable to the increased rate of growth and improved feed efficiency with modern genetic lines. Furthermore, Nyachoti et al. (2004) suggested that feed intake levels and patterns differ among genetics lines, and pigs with a high potential for lean tissue growth tend to have a lower voluntary feed intake compared to those with low muscle accretion rate. In our study, we speculate that lower Lys requirements could be associated to the genetic line utilized (DNA 600 × 241) having a 6% higher overall feed intake compared with PIC genetic lines as reported by Goncalves et al. (2017).

Determining the dietary crude protein requirement

Reduction of dietary CP by partially replacing the AA from intact protein sources, such as soybean-meal, with crystalline AA is a cost-effective strategy to improve the efficiency of N utilization.

Multiple finishing pig studies have shown that a high CP diet results in greater weight gain and higher carcass lean meat content compared with feeding a lower CP diet and similar AA levels (Adeola and Young, 1989; Kerr and Easter, 1995; Chiba et al., 2002; Ruusunen et al., 2007). Conversely, decreasing dietary CP has shown inconsistent results with reports of either no performance effects (Kerr et al., 2003; Ball et al. 2013; Tous et al., 2014) or negative effects, even when correct AA ratios are met (Rojo, 2011; Soto, 2018). Gomez et al. (2002) conducted a 55-d experiment to determine effects of two CP concentrations (16 or 12%) in conjunction with three intake levels (ad libitum, 90, or 80% of ad libitum intake) on growing barrow growth performance and plasma metabolites. Pigs fed the high CP diet had increased ADG, G:F, and final BW compared with pigs fed the low CP diet. As expected, with decreasing intake, there is a concomitant decrease in ADG. In addition, regardless of the feeding level, plasma urea concentration was decreased in pigs fed low CP compared with pigs fed high CP. Furthermore, Figueroa et al. (2002) conducted a 35-d experiment to determine the CP (11 to 16%) concentration below which growth performance was reduced in growing gilts fed low-CP, AA-fortified, corn-soybean meal diets. Reduction in CP concentration negatively impacted growth and carcass performance, with the most substantial reduction in ADG as the CP decreased from 12 to 11%, with a similar response in ADFI. Recent work conducted by Soto et al. (2017) studied the effects of feeding a 10 or 13% CP diet to finishing pigs and found significant performance reduction in pigs fed the diet with 10% CP. The results of our studies (Exp. 2 and 3) are consistent with the findings of Figueroa et al. (2002) and Soto et al. (2017), whom observed a 10 to 30% reduction in ADG in pigs fed dietary CP concentrations below 12%.

Figueroa et al. (2002) reported that pigs fed diets with lower CP concentration had a corresponding reduction in ADFI, with the lowest intake observed in pigs fed 11% CP.

Conversely, Soto et al. (2017) found no differences in ADFI associated to changes in dietary CP concentration. The results of our studies (Exp. 2 and 3) are consistent with Figueroa et al. (2002) where reduction in ADFI was observed when CP decreased. However, the highest ADFI corresponded with the highest ADG (12% CP) in Exp. 2, the highest intake (10 and 11% CP) did not correspond with the highest ADG (13% CP) in Exp. 3. As previously discussed, we speculate that variation ADFI in relation to CP reduction could be associated with the different genetics lines used (PIC 327 × 1050 and DNA 600 × 241 in Exp. 2 and Exp. 3, respectively). Pigs in Exp. 3 had 12% greater ADFI which could explain reaching their highest intake at a lower dietary CP level. Assuming an 85% digestibility of a corn-soybean meal diet (Dean, 2005), grams of digestible CP intake per kg of gain was 319.1 g with the 12% CP diet, where ADG and ADFI was maximized in Exp. 2. In Exp. 3, similar digestible CP intake per kg of gain (315.0 g) was reached and ADFI maximized with 10% CP diet. A digestible CP intake per kg of gain of 361.3 g was reached with the 13% CP diet, where ADG was maximized. However, regardless of feeding patterns, both genotypes maximized growth and carcass performance with diets containing 12 to 13% CP.

Concentrations of other essential AA may become limiting in low CP diets. Figueroa et al. (2006) indicated that lowering CP could result in a deficiency of other limiting AA for finishing pigs fed corn-soybean meal-based diets. However, all essential AA were above the SID levels recommended by NRC (2012) in our studies.

The current body of literature has suggested that there are several possible explanations for the negative effects on growth when low CP diets are fed. These include possible deficiency of non-essential AA or other nutrients not provided in low CP diets (Rojo, 2011; Ball et al., 2013; Mansilla, 2017). Furthermore, adding crystalline AA to a typical corn-soybean meal diet

leads to a reduction in the concentration of soybean meal. Thus, the question remains whether the reduced performance of pigs fed low CP diets is due to lower CP or decreased concentrations of soybean meal. Further research is needed to understand the reasons why pigs fed diets with seemingly adequate levels of AA, but with less than 12% CP have decreased growth and carcass performance.

In conclusion, the SID Lys requirement was 0.55 to 0.63% for pigs from 100-122 kg was depending on response criteria, and performance maximized in both genotypes with diets containing 12 to 13% dietary CP in pigs from 100 to 120 kg.

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TABLES AND FIGURES

Table 3.1. Diet composition in Exp. 1 (as-fed basis)[1]

Ingredient, %	Standardized ileal digestible Lys, %			
	0.45	0.55	0.65	0.75
Corn	86.66	84.87	83.18	81.38
Soybean meal (46.5% CP)	11.00	12.71	14.31	16.02
Choice white grease	0.50	0.50	0.50	0.50
Monocalcium P (21% P)	0.35	0.33	0.32	0.30
Limestone	0.95	0.94	0.93	0.93
Salt	0.35	0.35	0.35	0.35
L-Lys-HCl	---	0.08	0.15	0.23
DL-Met	---	---	0.01	0.01
L-Thr	---	0.03	0.05	0.08
L-Trp	---	0.01	0.01	0.02
Trace mineral premix[2]	0.10	0.10	0.10	0.10
Vitamin premix[3]	0.08	0.08	0.08	0.08
Phytase[2]	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	0.45	0.55	0.65	0.75
Ile:Lys	91	79	71	66
Leu:Lys	239	202	177	159
Met:Lys	43	38	33	31
Met & Cys:Lys	87	75	66	60
Thr:Lys	80	75	70	68
Trp:Lys	23.9	22.2	20.9	20.0
Val:Lys	107	93	83	75
His:Lys	67	57	51	46
Total Lys, %	0.54	0.65	0.75	0.86
SID Lys: NE, g/Mcal	1.74	2.14	2.53	2.93
NE NRC, kcal/kg	2,582	2,573	2,563	2,555
CP, %	12.4	13.2	13.9	14.6
Ca, %	0.47	0.47	0.47	0.47
P, %	0.38	0.38	0.39	0.39
Available P, %	0.22	0.22	0.22	0.22
Standardized digestible P, %	0.27	0.27	0.27	0.27

[1]Diets were fed from d 0 to 23 which correspond to 102.0 to 123.4 kg BW, respectively.

[2]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[3]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[4]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 400.8 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 3.2. Diet composition in Exp. 2 (as-fed basis)[1]

Item	CP, %			
	10	11	12	13
Ingredient, %				
Corn	93.09	89.87	86.63	83.38
Soybean meal (46.5% CP)	2.96	6.03	9.17	12.32
Choice white grease	0.55	1.00	1.45	1.90
Monocalcium P (21% P)	0.71	0.68	0.65	0.63
Limestone	0.97	0.98	0.96	0.92
Salt	0.35	0.35	0.35	0.35
L-Lys-HCl	0.52	0.43	0.33	0.23
DL-Met	0.10	0.07	0.04	0.02
L-Thr	0.19	0.15	0.11	0.06
L-Trp	0.06	0.05	0.03	0.01
L-Val	0.16	0.11	0.05	0.00
L-Ile	0.16	0.11	0.06	0.00
Trace mineral premix	0.10	0.10	0.10	0.10
Vitamin premix	0.08	0.08	0.08	0.08
Phytase[2]	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	0.66	0.66	0.66	0.66
Ile:Lys	65	65	65	65
Leu:Lys	132	143	154	165
Met:Lys	38	36	34	32
Met & Cys:Lys	62	62	62	62
Thr:Lys	66	66	66	66
Trp:Lys	19	19	19	19
Val:Lys	76	76	75	76
His:Lys	33	38	42	47
Total Lys, %	0.75	0.75	0.74	0.73
SID Lys: NE, g/Mcal	2.51	2.51	2.51	2.51
NE NRC, kcal/kg	2,443	2,443	2,443	2,443
CP, %	10.0	11.0	12.0	13.0
Ca, %	0.51	0.52	0.51	0.51
P, %	0.41	0.42	0.43	0.44
Available P, %	0.29	0.29	0.29	0.29
Standardized digestible P, %	0.31	0.32	0.32	0.32

[1]Diets were fed from d 0 to 20 which correspond to 109.4 to 126.8 kg BW, respectively.

[2]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[3]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[4]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 400.8 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 3.3 Diet composition in Exp. 3 (as-fed basis)[1]

Ingredient, %	CP, %				
	9	10	11	12	13
Corn	96.01	92.33	88.92	85.62	82.30
Soybean meal (46.5% CP)	0.47	3.96	7.27	10.42	13.57
Choice white grease	0.35	0.90	1.35	1.80	2.20
Monocalcium P (21% P)	0.60	0.58	0.55	0.53	0.50
Limestone	0.98	0.95	0.93	0.88	0.85
Salt	0.35	0.35	0.35	0.35	0.35
L-Lys-HCl	0.43	0.33	0.23	0.13	0.04
DL-Met	0.11	0.08	0.05	0.03	---
L-Thr	0.16	0.11	0.07	0.03	---
L-Trp	0.07	0.05	0.03	0.02	---
L-Val	0.11	0.06	---	---	---
L-Ile	0.19	0.13	0.07	0.02	---
Trace mineral premix[2]	0.10	0.10	0.10	0.10	0.10
Vitamin premix[3]	0.08	0.08	0.08	0.08	0.08
Phytase[4]	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00
Calculated analysis					
Standardized ileal digestible (SID) AA, %					
Lys	0.55	0.55	0.55	0.55	0.55
Ile:Lys	78	78	78	78	84
Leu:Lys	150	165	178	191	204
Met:Lys	48	45	43	41	39
Met & Cys:Lys	80	80	80	80	80
Thr:Lys	70	70	70	70	73
Trp:Lys	22	22	23	22	23
Val:Lys	79	79	79	88	97
His:Lys	35	40	45	50	55
Total Lys, %	0.65	0.65	0.64	0.63	0.62
SID Lys:NE, g/Mcal	2.08	2.08	2.08	2.08	2.08
NE NRC, kcal/kg	2,451	2,451	2,451	2,451	2,451
CP, %	9.0	10.0	11.0	12.0	13.0
Ca, %	0.50	0.50	0.50	0.50	0.50
P, %	0.41	0.42	0.43	0.43	0.44
Available P, %	0.26	0.26	0.26	0.26	0.26
Standardized digestible P, %	0.29	0.29	0.30	0.30	0.30

[1]Diets were fed from d 0 to 26 which correspond to 111.8 to 134.6 kg BW, respectively.

[2]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[3]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[4]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 400.8 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 3.4. Chemical analysis of experimental diets in Exp. 1 (as-fed basis)[1]

	Standardized ileal digestible Lys, %			
Item, %	0.45	0.55	0.65	0.75
DM	87.7	87.7	87.7	87.8
CP	12.1	12.3	12.9	14.2
Ca	0.66	0.68	0.72	0.76
P	0.40	0.39	0.39	0.40
Ether extract	4.2	3.7	3.4	3.5
Ash	3.57	4.35	4.04	4.18
Total AA				
Lys	0.54	0.65	0.76	0.82
Ile	0.47	0.54	0.57	0.60
Leu	1.16	1.29	1.33	1.36
Met	0.21	0.24	0.25	0.26
Met & Cys	0.45	0.50	0.53	0.54
Thr	0.46	0.50	0.57	0.58
Trp	0.12	0.14	0.16	0.17
Val	0.59	0.65	0.69	0.70
His	0.30	0.33	0.36	0.36
Phe	0.61	0.69	0.74	0.74
Free Lys	0.01	0.05	0.09	0.11

[1]Diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of the trial and 3 d prior to the end of the trial and stored at -20°C, then amino acid analysis was conducted on composite samples by Ajinomoto Heartland, Inc. (Chicago, IL). Samples of the diets were also submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM, CP, Ca, P, ether extract, and ash.

Table 3.5. Chemical analysis of experimental diets in Exp. 2 (as-fed basis)[1]

Item, %	CP, %			
	10	11	12	13
DM	85.3	85.4	85.4	85.7
CP	9.0	10.9	11.9	13.1
Ca	0.72	0.62	0.60	0.61
P	0.46	0.56	0.48	0.50
Ether extract	3.7	5.4	5.1	5.3
Ash	4.0	4.2	4.0	4.1

[1]Multiple diet samples were collected from each diet throughout the study, homogenized, and then subsampled for analysis (Ward Laboratories, Inc. Kearney, NE).

Table 3.6. Chemical analysis of experimental diets in Exp. 3 (as-fed basis)[1]

	CP, %				
Item. %	9	10	11	12	13
DM	86.0	86.1	86.2	86.5	86.5
CP	8.9	10.0	10.8	11.9	12.9
Ca	0.63	0.69	0.57	0.61	0.61
P	0.41	0.41	0.41	0.41	0.42
Extract ether	3.6	3.7	3.7	4.1	4.0
Ash	2.0	2.3	2.4	2.8	2.7
Total amino acids					
Lys	0.55	0.58	0.55	0.59	0.59
Ile	0.45	0.46	0.54	0.48	0.57
Leu	0.96	1.02	1.15	1.21	1.32
Met	0.27	0.26	0.24	0.24	0.23
Met & Cys	0.46	0.47	0.46	0.48	0.48
Thr	0.46	0.46	0.43	0.48	0.47
Trp	0.12	0.12	0.13	0.13	0.13
Val	0.51	0.55	0.60	0.61	0.66
His	0.22	0.25	0.26	0.31	0.33
Phe	0.47	0.52	0.57	0.65	0.69

[1]Diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of the trial and 3 d prior to the end of the trial and stored at -20°C, until analysis. Amino acid analysis was conducted on composite samples by Ajinomoto Heartland, Inc. (Chicago, IL). Samples of the diets were also submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM, CP, Ca, P, ether extract, and ash.

Table 3.7. Effects of standardized ileal digestibility (SID) Lys on growth and carcass performance of finishing pigs over 100 kg (Exp. 1)[1]

	SID Lys, %					Probability, $P <$	
Item	0.45	0.55	0.65	0.75	SEM	Linear	Quadratic
BW, kg							
d 0	102.0	102.0	102.0	102.1	0.44	0.856	0.692
d 23	121.8	124.9	123.8	123.4	0.72	0.423	0.167
d 0 to 20							
ADG, kg	0.86	0.97	0.94	0.92	0.027	0.260	0.015
ADFI, kg	2.79	3.01	2.85	2.87	0.049	0.769	0.041
G:F	0.307	0.323	0.329	0.319	0.0071	0.191	0.058
SID Lys, g/kg gain	14.7	17.0	19.8	23.6	0.46	0.001	0.110
SID Lys, g/d	12.6	16.6	18.5	21.5	0.28	0.001	0.074
Carcass characteristics							
HCW, kg	89.9	92.7	92.0	92.1	0.97	0.173	0.182
Carcass yield, %	73.7	74.2	74.1	74.5	0.25	0.051	0.666
Backfat[2], mm.	15.7	16.3	15.8	15.0	0.36	0.154	0.074
Loin depth[2], mm.	63.7	62.7	64.2	64.4	1.13	0.455	0.611
Lean[2], %	54.9	54.5	54.9	55.3	0.24	0.128	0.121
Carcass performance							
Carcass ADG[3], kg	0.63	0.72	0.70	0.68	0.020	0.179	0.014
Carcass G:F[4]	0.226	0.240	0.244	0.238	0.005	0.095	0.063

[1]A total of 253 pigs (DNA 600 × 241; initially 102.0 kg BW) were used with 8 pigs per pen and 8 replications per treatment.
[2]Adjusted using HCW as a covariate.
[3]Carcass average daily gain = overall ADG × carcass yield.
[4]Carcass G:F = carcass average daily gain/overall average feed intake.

Table 3.8. Effects of increasing dietary CP concentration on growth and carcass performance of finishing pigs over 100 kg (Exp. 2)[1,2,3]

	CP, %					Probability, $P <$	
Item	10	11	12	13	SEM	Linear	Quadratic
BW, kg							
d 0	109.4	109.4	109.4	109.4	---	---	---
d 20	125.6	126.5	127.7	127.4	0.61	0.022	0.341
d 0 to 20							
ADG, kg	0.77	0.86	0.91	0.90	0.029	0.001	0.080
ADFI, kg	2.58	2.72	2.84	2.76	0.054	0.014	0.060
G:F	0.299	0.317	0.323	0.328	0.0081	0.020	0.452
Digestible CP intake, g/kg gain	287.1	297.9	319.1	338.9	8.03	<0.001	0.322
Carcass characteristics							
HCW, kg	94.0	94.0	95.5	95.0	0.47	0.040	0.640
Carcass yield, %	74.8	74.3	74.8	74.6	0.24	0.780	0.510
Carcass performance							
Carcass ADG[4], kg	0.60	0.65	0.69	0.68	0.016	0.001	0.070
Carcass G:F[5]	0.233	0.239	0.242	0.246	0.0046	0.050	0.880

[1]A total of 224 pigs (PIC 1050 × 327; initially 109.4 kg BW) were used in a 20-d experiment with 7 pigs per pen.
[2]Treatment with 10% CP had 7 replications and 8 replications for the treatments with 11, 12 and 13% CP.
[3]Allotment weight used as a covariate for growth and carcass performance variables.
[4]Carcass average daily gain = overall ADG × carcass yield.
[5]Carcass G/F = carcass average daily gain/average feed intake.

Table 3.9. Effects of increasing dietary crude protein concentration on growth and carcass performance of finishing pigs over 100 kg (Exp. 3)[1]

	CP, %						Probability, $P <$	
Item	9	10	11	12	13	SEM	Linear	Quadratic
BW, kg								
d 0	111.8	111.8	111.8	111.8	111.8	0.74	0.948	0.961
d 26	132.8	133.9	135.0	135.5	135.8	0.80	0.463	0.001
D 0 to 26								
ADG, kg	0.81	0.85	0.89	0.91	0.93	0.022	0.508	0.001
ADFI, kg	2.99	3.14	3.14	3.12	3.11	0.055	0.073	0.322
G:F	0.270	0.271	0.285	0.293	0.299	0.0044	0.336	0.001
Digestible CP intake, g/kg gain	283.5	315.0	328.2	355.8	361.3	5.77	0.107	0.001
Carcass characteristics								
HCW, kg	99.7	100.7	101.4	101.6	101.3	0.87	0.344	0.074
Carcass yield, %	75.0	75.2	75.1	75.0	74.6	0.46	0.533	0.638
Backfat[2], mm.	18.3	18.5	17.9	18.2	17.8	0.46	0.922	0.424
Loin depth[2], mm.	63.5	62.9	63.2	63.5	63.9	0.89	0.538	0.544
Lean[2], %	53.3	53.1	53.3	53.3	53.4	0.27	0.424	0.531
Carcass performance								
Carcass ADG[3], kg	0.61	0.64	0.67	0.68	0.69	0.017	0.461	0.001
Carcass G:F[4]	0.203	0.203	0.215	0.220	0.223	0.0035	0.535	0.001

[1]A total of 238 pigs (DNA 600 × 241; initially 111.8 kg BW) were used in a 26-d experiment with 7-8 pigs per pen and 6 replications per treatment

[2]Adjusted using HCW as a covariate.

[3]Carcass average daily gain = overall ADG × carcass yield.

[4]Carcass G:F = overall average feed intake/carcass average daily gain.

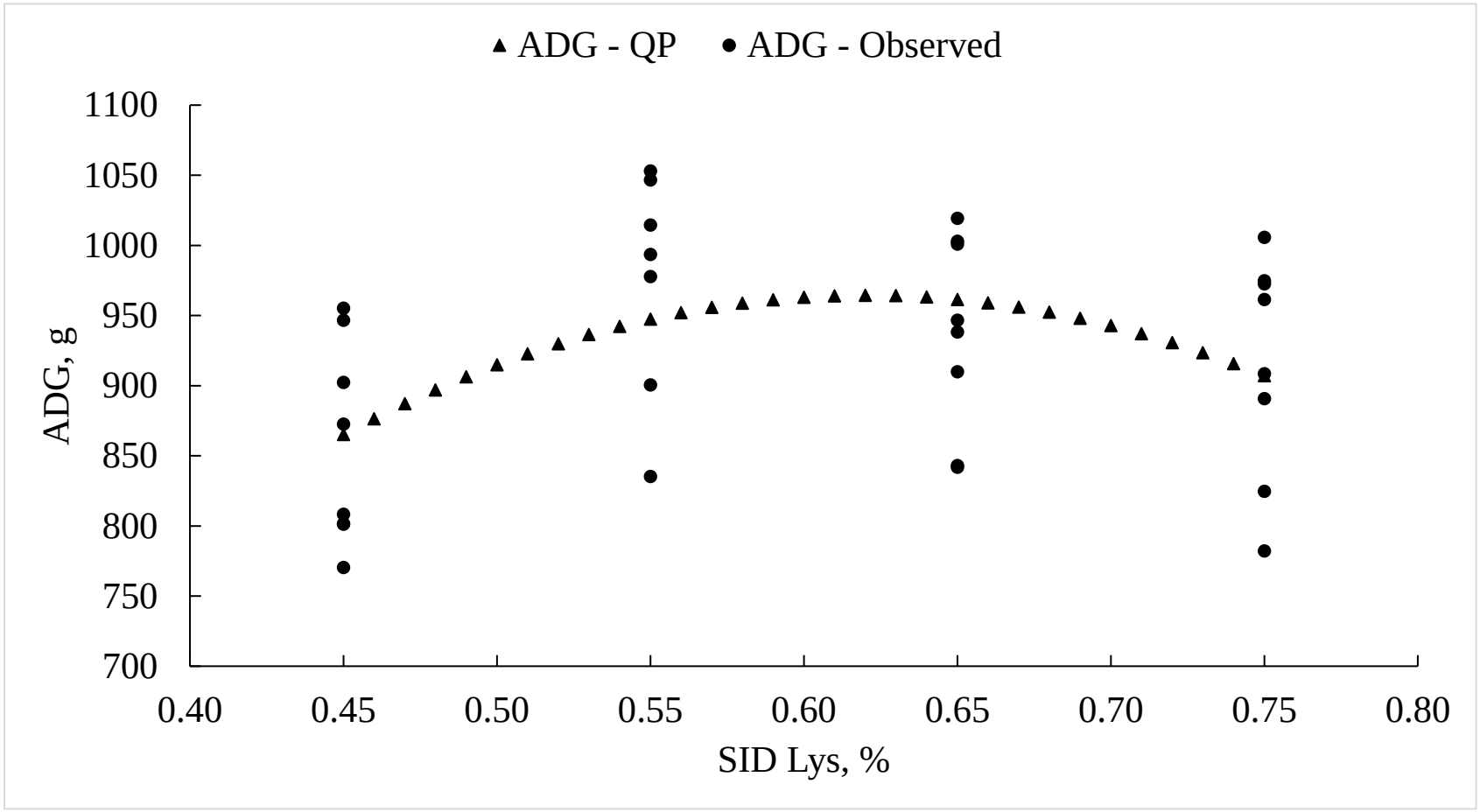

Figure 3.1. Estimation of standardized ileal digestible (SID) Lys to maximize ADG for mixed gender finishing pigs. A total of 253 pigs (DNA 600 × 241, initially 102.0 kg BW) were used in a 23-d trial. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit to estimate SID Lys level to maximize ADG. The QP model predicted 95, 98, and 100% of maximum growth at 0.50, 0.55, and 0.62% SID Lys, respectively. The QP model equation was: ADG, g = -350.1334 + 4236.996 × (% SID Lys) – 3414.007 × (% SID Lys)^2.

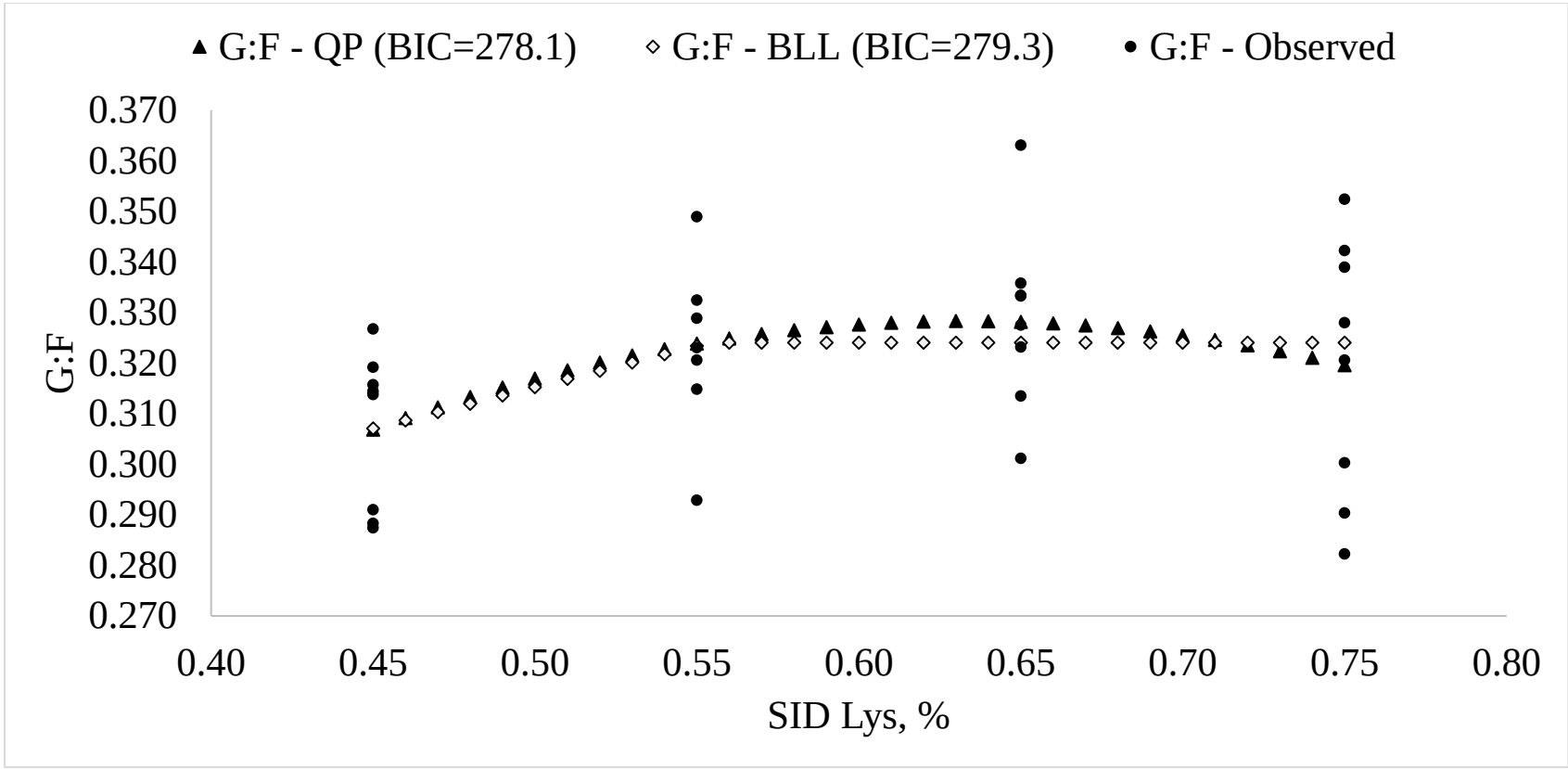

Figure 3.2. Estimation of standardized ileal digestible (SID) Lys to maximize G:F for mixed gender finishing pigs. A total of 253 pigs (DNA 600 × 241, initially 102.0 kg BW) were used in a 23-d trial. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fit to estimate SID Lys level to maximize G:F. The QP and BLL models had a comparable fit for G:F (BIC = 278.2 vs 279.3, QP and BLL, respectively). The QP model predicted 95, 98, and 100% of maximum feed efficiency at 0.48, 0.54, and 0.63% SID Lys, respectively. The QP model equation was: G:F = 71.9 + 809.67 × (SID Lys, %) – 639.24 × (SID Lys, %)^2. The BLL model predicted no further improvement in G:F over 0.55% SID Lys. The BLL model equation was: G:F = 324.1 – 163.24 × (0.554 - SID Lys, %) if SID Lys < 0.554%, and 324.1 if SID Lys > 0.5544.

Chapter 4 – The effects of soybean meal concentration, dietary electrolyte balance, choline, and potassium supplementation on growth and carcass performance in 110 kg and heavier finishing pigs

ABSTRACT

Four experiments were conducted to determine if the negative effects of feeding low CP diets to pigs over 100 kg could be mitigated by dietary soybean meal (SBM), dietary electrolyte balance (dEB), choline, or K. In Exp. 1, 280 pigs were used in a 23-d trial with 7 to 8 pigs per pen and 6 pens per treatment. Treatments consisted of a diet with 12% CP containing 5 levels of SBM (10.6, 7.7, 4.9, 2.7, and 0%) and a negative control diet with 4.0% SBM and 10% CP. Decreasing SBM while maintaining 12% CP marginally decreased ADG (linear, $P = 0.061$), increased ADFI (linear, $P = 0.018$), and worsened G:F (linear, $P < 0.001$). Decreasing SBM decreased carcass ADG (linear, $P = 0.037$) and worsened carcass G:F (linear, $P < 0.001$). Feed intake was decreased ($P = 0.007$) in pigs fed 12% CP and 10.6% SBM compared with pigs fed 10% CP and 4.0% SBM, resulting in a marginal improvement in G:F ($P = 0.062$) and improved carcass G:F ($P = 0.048$) for pigs fed the 12% CP, 10.6% SBM diet. In Exp. 2, 288 pigs were used in a 20-d trial with 7 to 8 pigs per pen and 9 pens per treatment. Treatments were arranged in a 2 × 2 factorial with main effects of CP (10 or 13%) and dEB (48 or 107 mEq/kg). Pigs fed 13% CP diets had greater ADG ($P = 0.001$), final BW ($P = 0.037$), G:F, HCW, HCW ADG ($P < 0.001$), and HCW G:F ($P = 0.001$) compared with pigs fed 10% CP diets, but dEB had no impact. In Exp. 3, 284 pigs were used in a 26-d trial with 7 to 8 pigs per pen and 9 pens per treatment. Treatments included a 12% CP, positive control diet with 10.6% SBM, a 10% CP;

negative control diet with 4.0% SBM; negative control with added 0.03% choline chloride; or negative control with added 0.24% potassium chloride. There was no evidence for differences in ADG or ADFI; however, there was a marginal improvement in G:F (P = 0.085) for pigs fed the positive control diet compared to pigs fed 10% CP. Supplementing diets with choline or K did not influence performance. In Exp. 4, 254 pigs were used in a 19-d trial with 7 to 8 pigs/pen and 8 pens/treatment. Treatments were arranged in a 2 × 2 factorial with main effects of CP (12% or 10%) and choline (none or added [1,814 mg/kg]). Pigs fed diets with 12% CP had marginally increased ADG (P = 0.076) compared with pigs fed 10% CP which resulted in a heavier final BW (P=0.036) and improved G:F (P=0.020). Adding 1,814 mg/kg of choline did not influence growth performance. In summary, these results suggest that choline, K, and dEB do not appear to be the reason why performance is reduced when SBM concentration is decreased in low CP diets fed to pigs over 110 kg BW.

Key words: choline, crude protein, growth, finishing pigs, potassium, soybean meal

INTRODUCTION

Soybean meal (SBM) is the main protein source utilized in animal production in the world. One of the main reasons for the high usage of SBM is the unique composition of AA, complementing the AA compositions of many cereal grains (Stein et al., 2008).

Development of low protein, AA fortified diets has resulted in lowering the concentration of SBM. However, research has shown that decreasing dietary CP may compromise growth performance in finishing pigs, even when all nutrient requirements are met (Shelton et al., 2001; Rojo, 2011). Soto (2018) reported reduction in growth and carcass performance when finishing pigs are fed corn-soybean meal diets formulated below 12% CP, fortified with all AA at or above

minimum requirement estimates relative to Lys. Research has suggested that SBM contains biologically active compounds that may be important for growth performance (Rochell et al., 2015). From a dietary composition perspective, there is a proportional decrease of dietary electrolyte balance (dEB) and a significant reduction of choline and K when diets are fortified with crystalline AA. Research has shown that dEB alters the acid-base status and may impact swine performance (Patience et al., 1987; Guzman-Pino et al., 2015). Furthermore, dietary choline and K play essential roles in multiple physiological processes (NRC, 2012).

However, the question remains whether the reduced performance of pigs fed low CP diets is due to the low CP per se, decreased concentrations of SBM, or reductions in dEB, choline, or K that occur when SBM is lowered from the diet. Thus, the objective of these studies was to determine the effects of dietary SBM concentration, dEB, choline, and K in diets with moderate and low levels of CP on growth and carcass performance of pigs over 110 kg BW.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. All experiments were conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The facility was totally enclosed and environmentally regulated. Each pen (2.44 × 3.05 m) was equipped with a dry single-sided feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line and 1-cup waterer. Pens were located over a completely slatted concrete floor with a 1.20 m deep pit underneath for manure storage. Daily feed additions to each pen were accomplished through a

robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens. Prior to the experimental diets pigs were fed a corn-soybean meal-based diet with 14.2% CP, 0.72% SID Lys, and 2,535 kcal/kg of NE in all experiments. In addition, pigs were provided ad libitum access to water and to feed in meal form throughout the experiments.

Experiment 1

A total of 280 pigs (DNA 600 × 241, with initial and final BW of 114.2 ± 2.2 and 135.6 ± 2.5 kg, respectively) were used in a 23-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 6 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 6 pens of 7 to 8 pigs per pen with a similar number of barrows and gilts in each pen.

Dietary treatments consisted of 5 concentrations of SBM (10.6, 7.7, 4.9, 2.7, and 0%) with 12% CP and a negative control treatment with 4.0% SBM and 10% CP. To create the experimental diets, a 12% CP, corn-soybean meal diet with 10.6% SBM and 0.13% L-Lys HCl was formulated. Then, a 12% CP, corn-corn gluten meal based diet with 0.39% L-Lys HCl and no SBM was formulated. The 10.6 and 0% SBM diets were blended to create the 7.7, 4.9, and 2.7% SBM diets and maintaining 12% CP (Table 4.1). Lastly, a 10% CP corn-soybean meal diet with 4.0% SBM and 0.33% L-lysine HCl was formulated. In all diets, ratios of other AA to Lys were maintained well above minimum requirement estimates to ensure that other AA relative to Lys were not limiting (NRC, 2012). Diets contained 2,659 kcal NE/kg by adjusting the amount of fat as corn, corn gluten meal, and SBM changed in the diet.

Experiment 2

A total of 288 pigs (PIC 327 × 1050, with initial and final BW of 109.6 ± 1.6 and 124.8 ± 2.1 kg, respectively) were used in a 20-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 4 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 9 pens of 7 to 8 pigs per pen with a similar number of barrows and gilts in each pen.

Dietary treatments were arranged in a 2 × 2 factorial with main effects of CP (10 or 13%) and dEB (48 or 107 mEq/kg). To create the experimental diets, a 13% CP, corn-soybean meal diet was formulated to include a moderate level (0.23%) of L-Lys HCl with other AA at or above minimum ratios relative to Lys. Dietary electrolyte balance in this diet was 107 mEq/kg. Then, dietary CP was decreased to 10% by increasing the inclusion of crystalline AA resulting in a diet with a dEB of 48 mEq/kg. Again, all AA were at or above minimum ratios relative to Lys. To complete the factorial, CaCl was added (0.43%) to the 13% CP diet to lower dEB from 107 to 48 mEq/kg and sodium bicarbonate was added (0.51%) to the 10% CP diet to increase dEB from 48 to 107 mEq/kg (Table 4.2). All diets contained 2,626 kcal NE/kg by adjusting the amount of fat as the amounts of corn and SBM changed in the diet.

Experiment 3

A total of 284 pigs (DNA 600 × 241, with initial and final BW of 112.2 ± 2.5 and 133.8 ± 2.7 kg, respectively) were used in a 26-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 4 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 9 pens of 7 to 8 pigs per pen with a similar number of barrows and gilts in each pen.

Dietary treatments included a 12% CP positive control diet with 10.6% SBM, a 10% CP, negative control diet with 4.0% SBM, the negative control with added choline or K to equal the concentration provided by the 12% CP positive control diet; with 816 mg/kg of choline and 0.51% K, which represents 2.7 and 3 times NRC (2012) requirements, respectively. To create the experimental diets, a 12% CP corn-soybean meal diet with an inclusion of 10.6% SBM with 0.13% L-Lys HCl was formulated. Then, a negative control, 10% CP corn-soybean meal diet with 4.0% inclusion of SBM with 0.33% L-Lys HCl was formulated. Lastly, the negative control diet was supplemented with 0.03% choline chloride (60%) or 0.24% KCl so that the level of choline or K matched that in the 12% CP diet. In all diets, ratios of other AA to Lys were maintained well above minimum levels to ensure that other AA were not limiting. (Table 4.3). All diets contained 2,659 kcal NE/kg by adjusting the amount of fat as the amounts of corn and SBM changed in the diet.

Experiment 4

A total of 254 pigs (DNA 600 × 241, with initial and final BW of 110.5 ± 2.3 and 122.7 ± 2.2 kg, respectively) were used in a 19-d trial. Pens of pigs were weighed, and pens were randomly assigned to 1 of 4 dietary treatments in a completely randomized block design blocked by initial average pen BW. Each treatment consisted of 8 pens of 7 to 8 pigs per pen with a similar number of barrows and gilts in each pen.

Dietary treatments were arranged in a 2 × 2 factorial with main effects of CP (12 or 10%) and choline (none or added) to reach a final diet concentration of choline of 1,814 mg/kg of diet based on NRC (2012). To create the experimental diets, a 12% CP, corn-soybean meal diet with an inclusion of 10.6% SBM and 0.13% L-Lys HCl was formulated. Then, a 10% CP, corn-

soybean meal diet with 4.0% inclusion of SBM and 0.33% L-Lys HCl was formulated. Equivalent to the positive and negative control diets from Exp. 3. Then the high and low CP diets were supplemented with 0.20 or 0.23% choline chloride, respectively, to provide a total of 1,814 mg of choline per kg in the final diet. The 12% CP diet contained a basal level of choline that was approximately 2.7 times the NRC (2012) requirement. The supplemental amount of choline increased the concentration to approximately 6.0 times the choline requirement estimates for finishing pigs suggested by NRC (2012). In all diets, ratios of AA to Lys were maintained well above minimum levels to ensure that AA were not limiting. (Table 4.4). All diets contained 2,659 kcal NE/kg by adjusting amount of fat the ratios of corn and SBM changed in the diet.

Data collection

Pens of pigs were weighed and feed disappearance was measured weekly and at the end of each experiment to calculate ADG, feed disappearance, and G:F. Prior to marketing, pigs were individually tattooed with a unique ID number to allow for carcass measurements to be recorded on a pig basis in all experiments, except Exp. 4. At the end of the first three experiments (d 23, 20, and 26 for Exp. 1, 2, and 3, respectively), individual weights were taken, and pigs were transported to a USDA-inspected packing plants (National Foods Holding Sioux Center, IA in Exp. 1; Farmland Crete, NE in Exp.2; Triumph St. Joseph, MO in Exp. 3) for processing and carcass data collection. In Exp. 1 and 2, carcass measurements only included HCW. In Exp. 3, carcass measurements included HCW, loin depth, backfat, and percentage lean. In all experiments, carcass yield was calculated by dividing the individual HCW at the plant by final live weight at the farm.

Diet Sampling and Analysis

In all experiments, diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of each trial and stored at -20°C until analysis. Diet samples were submitted to Cumberland Valley Analytical Service (Hagerstown, MD) in Exp. 1, 3, and 4, and Ward Laboratories, Inc. (Kearney, NE) in Exp. 2. In all experiments, diets were analyzed for DM (method 935.29; AOAC Int., 2012), CP (method 990.03; AOAC Int., 2012), ash (method 942.05; AOAC Int., 2012), ether extract (method 920.39 a; AOAC Int., 2012 for preparation and ANKOM XT20 Fat Analyzer [Ankom Technology, Fairport, NY], Ca, and P (method 968.08 b; AOAC Int., 2012 for preparation using ICAP 6500 [ThermoElectron Corp., Waltham, MA]). In addition, diet samples of Exp. 1 were submitted for total AA analysis (method 994.12; AOAC Int., 2012) by Ajinomoto Heartland, Inc. (Chicago, IL). In Exp. 3, diets samples were submitted for K analysis (method 985.01; AOAC Int., 2012) and choline analysis (method 994.14; AOAC Int., 2012) by Ward Laboratories, Inc. (Kearney, NE) and Barrow-Agee (Memphis, TN), respectively.

Statistical Analysis

In all experiments, data were analyzed using the PROC GLIMMIX procedure in SAS (SAS Institute, Inc., Cary, NC) with pen as the experimental unit and initial BW as a blocking factor. Dietary treatments were the fixed effect and block served as the random effect in the analysis. In Exp. 1, preplanned linear and quadratic orthogonal contrast were conducted using coefficients for unequally spaced treatment and used to determine the main effects of reducing soybean meal concentration. In addition, a contrast was conducted to compare the positive control with 12% CP to the negative control diet with 10% CP. In Exp. 2 and 4, main effects of

CP and dEB, and CP and choline as well as their interactions were tested, respectively. In Exp. 3, a contrast was conducted to compare the positive control diet with 12% CP to the three diets with 10% CP. In the same experiment, HCW served as a covariate for the analysis of backfat, loin depth, and lean percentage. Model assumptions were checked using studentized residuals and were appropriately met. Results were considered significant at $P < 0.05$ and a marginally significant between $P > 0.05$ and $P \leq 0.10$.

RESULTS

The analyzed nutrient and total AA of diets in Exp. 1, 2, 3, and 4 (Tables 4.5, 4.6, 4.7, and 4.8, respectively) were reasonably consistent with formulated estimates. In Exp. 3, the analyzed concentrations of choline were lower than formulated values, suggesting that either the corn or soybean meal contained less choline than NRC (2012) suggested levels. However, choline increased in the choline supplemented diet and was similar to the analyzed value in the positive control diet.

Experiment 1

For overall growth performance (d 0 to 23), decreasing SBM marginally decreased (linear, $P = 0.061$) ADG with the lowest response observed in pigs fed less than 4.9% SBM (Table 4.9). Pigs fed decreasing SBM had increased (linear, $P = 0.018$) ADFI, worsened (linear, $P < 0.05$) G:F. There was no evidence for differences in ADG for pigs fed the negative control diet with 10% CP and 4.0% SBM compared with pigs fed the diet with 12% CP and 10.6% SBM. Nonetheless, ADFI was decreased ($P = 0.007$) in pigs fed the diet with 12% CP and 10.6% SBM compared with pigs fed the diet with 10% CP and 4.0% SBM. Therefore, there was a

marginal improvement ($P < 0.10$) in G:F for pigs fed the diet with 12% CP and 10.6% SBM compared with pigs fed the negative control diet with 10% CP and 4.0% SBM.

For carcass characteristics, lowering dietary SBM decreased (linear, $P = 0.037$) carcass ADG, worsened (linear, $P < 0.05$) carcass G:F. There was no evidence for differences in carcass ADG for pigs fed the negative control diet with 10% CP and 4.0% SBM compared with the pigs fed the diet with 12% CP and 10.6% SBM. Nonetheless, feeding the high CP diet improved ($P = 0.048$) carcass G:F compared with pigs fed the negative control diet with 10% CP and 4.0% SBM.

Experiment 2

For overall growth performance (d 0 to 20), a marginal significant CP × dEB interaction was observed for ADFI ($P = 0.081$) because intake was numerically reduced when dEB increased for the pigs fed 10% CP whereas intake increased as dEB was increased for the pigs fed 13% CP. For dietary CP, pigs fed diets with 13% CP had increased ($P = 0.001$) ADG compared with pigs fed diets with 10% CP which resulted in a heavier ($P = 0.037$) final BW (Table 4.10). Pigs fed the diets with 13% CP had improved ($P < 0.001$) G:F compared with pigs fed the 10% CP diets.

For carcass performance, pigs fed the diets with 13% CP had increased ($P < 0.002$) carcass ADG and G:F compared with pigs fed the 10% CP diets. No main effects for either CP or dEB were observed for HCW and carcass yield.

Experiment 3

For overall growth performance (d 0 to 26), there was no evidence for differences in ADG or ADFI for pigs fed the positive control diet with 12% CP and 10.6% SBM compared with pigs fed the diets containing 10% CP and 4% SBM (Table 4.11). However, there was a marginal improvement ($P = 0.085$) in G:F for pigs fed the positive control diet with 12% CP and 10.6% SBM compared to pigs fed diets with 10% CP and 4.0% SBM. However, adding choline or K to the negative control diet did not influence pig performance.

For carcass characteristics, there was no evidence for differences in HCW, yield, backfat, loin depth, or lean percentage. However, pigs fed the positive control diet with 12% CP and 10.6% SBM had increased ($P = 0.028$) carcass G:F compared with the mean of pigs fed the diets with 10% CP and 4.0% SBM.

Experiment 4

For overall growth performance (d 0 to 19), there was no evidence for CP × choline interaction. Pigs fed diets with 12% CP had marginally increased ($P = 0.076$) ADG compared with pigs fed diets with 10% CP which resulted in a heavier ($P = 0.036$) final BW (Table 4.12). Furthermore, pigs fed the diets with 12% CP had improved ($P = 0.020$) G:F compared with pigs fed the 10% CP diets.

DISCUSSION

The effects of soybean meal concentration

Soybean meal is a major protein ingredient used in swine diets, and represents the standard to which all other protein sources are measured (Shelton et al., 2001). Soybean meal's

AA profile, high digestibility, and minimal variation in nutritional composition make it an excellent protein source (Van Kempen et al., 2002). In addition, SBM contains several biologically active compounds, such as isoflavones, saponins, proteins, and peptides, that may also be important for growth performance (Omoni and Aluko, 2005; Rochell et al., 2015).

Renewed interest in lowering dietary CP by increasing the concentration of dietary crystalline AA has resulted in reductions of AA sources such as SBM. Furthermore, research has shown that there are limitations to the extent of CP reduction that can be done before performance is reduced. Knowles et al. (1998) reported that when CP is reduced 3 percentage units, performance is comparable to finishing pigs fed control corn-soybean meal diet with 15% CP. However, several reports concur that reducing CP by over 4% lead to reduction of ADG and G:F, even when all nutrient requirement are met (Kerr and Easter, 1995; Shelton et al., 2001).

Whereas multiple reports have attempted to evaluate the effects of lowering CP in finishing pig diets, research evaluating SBM concentration with fixed levels of CP is limited, and focused on partial or full replacement of SBM with other protein sources. Partanen (1998) suggested that replacing 33 to 67% of SBM with meat and bone meal negatively impacted ADG and G:F. Furthermore, Shelton et al. (2001) conducted a 90-d experiment to evaluate nine protein sources on growth and carcass performance of growing-finish pigs and reported that feeding a corn diet fortified with crystalline AA reduced performance during the grower and early-finishing periods, but not during the late-finishing period. However, carcass muscling was reduced, and carcass fat was increased among pigs fed the corn-AA diet compared with pigs fed diet containing SBM. Dean (2005) conducted a 47-d experiment to determine the effects of two CP concentrations (13.5 or 9.5%) in conjunction with two protein sources (SBM or soy protein isolate [SPI]) on growth and carcass performance of finishing barrows. Pigs fed the high CP-

SBM diet had less fat and were leaner than pigs fed the high CP-SPI diet, with pigs fed the low CP-SBM diet being intermediate. In addition, the results indicate that pigs fed low CP diets supplemented with crystalline AA may have reduced growth performance and more carcass fat than those fed higher CP diets. The results of our study suggest that growth and carcass performance are reduced when low SBM diets are fed, which agree with the results of Partanen et al. (1996) and Shelton et al. (2001). In addition, Dean (2005) reported an increase in ADFI when CP was decreased leading a poorer G:F, which agrees with our results. Furthermore, lowering CP can lead to increased fat deposition. Unfortunately, due to packing plant limitations, carcass backfat or percentage lean were not collected for this study. However, we have not observed increases in fat deposition by lowering CP in multiple studies with finishing pigs conducted by our group (Soto et al., 2017). Reports in the literature suggest that formulating diets on a NE basis can prevent an increase in carcass fat when CP is lowered (Le Bellego et al., 2001). The NE system was used to formulate diets in our studies.

Corn gluten meal (CGM) is a co-product of the wet milling industry where it is produced after most of the starch and germ have been removed and some of the fiber has been separated. The remaining CGM contains 60% CP and has a low concentration of NDF (Stock, 2000). According to Almeida and Stein (2011), indispensable AA in CGM is not ideal relative to the requirements of pigs. However, if corn gluten meal-containing diets are fortified with crystalline AA, diets are then balanced in AA and may be formulated with an inclusion up to 15% without impacting performance (Mahan, 1993). Therefore, a corn-CGM with supplemental AA diet should simulate AA concentrations of a corn-soybean meal diet.

Fully replacing SBM with CGM while keeping CP constant in finishing pigs diets resulted in a 5 and 10% reduction in ADG and G:F, respectively. Our results suggest that

reducing SBM below 10.6% in a diet containing 0.55% SID Lys could represent one of the reasons why we observed decreased growth performance in finishing pigs fed low CP diets. Furthermore, worsening growth performance as SBM was progressively replaced with CGM may be due to an increase of Leu:Lys and subsequent Ile:Lys imbalance, as suggested by Fu (2005). However, diets were supplemented with crystalline Ile resulting in a 75% SID Ile:Lys. Additionally, it may suggest that one or more biologically active compounds found within SBM may be contributing to the responses observed (Omoni and Aluko, 2005; Rochell et al., 2015).

The effects of dietary electrolyte balance

According to Mongin (1981), dEB represents the dietary mineral balance between fixed cations and anions (Na +K-Cl in mEq/kg of diet) which determines the diet acidogenicity or alkalinogenicity. It is well known that dEB alters the body acid-base status and subsequently may impact animal performance. Extensive research performed in swine would indicate positive performance effects when dEB is modified (Patience et al., 1987; Guzman-Pino et al., 2015). Furthermore, increasing dEB has previously been shown to reduce incidence of nonambulatory and noninjured swine, improve meat quality, and reduce the incidence of gastric ulcers (Ahn et al., 1992; Edwards et al., 2010). According to the NRC (2012), the optimal dEB for pigs is about 250 mEq/kg of diet. Early work conducted by Patience et al. (1987) suggested that growth appeared to be optimal within a dEB range of 0 to 341 mEq/kg, however, ADG, ADFI, and G:F were maximized at 175 mEq/kg in 15 kg pigs. Haydon and West (1990) suggested that nutrient digestibility was improved in growing pigs fed diets with dEB concentrations ranging from 250 to 400 mEq/kg, and speculated that dEB may alter gut pH, enzymatic activity, or the absorption mechanism. In addition, nutritional digestibility improvements by increasing dEB concentrations

have been confirmed by others (Guzman-Pino et al., 2015; Lei et al., 2017). Haydon et al. (1990) reported that ADFI was increased as dEB increased from 25 to 400 mEq/kg of diet, however, ADG, ADFI, and G:F were maximized at 250 mEq/kg of diet in both growing and finishing pigs during periods of high ambient temperature. Conversely, Wondra et al. (1995) reported that ADG, ADFI, and G:F were not affected in growing-finishing pigs fed diets with dEB ranging from 134 to 231 mEq/kg diet. Similarly, Edwards et al. (2010) reported that growth and carcass performance were not affected in finishing pigs fed diets with either 121 or 375 mEq/kg. These finding are consistent with our results, where pigs fed diets with dEB ranging from 48 to 107 mEq/kg had no effects on growth or carcass performance. Furthermore, Wondra et al. (1995) reported that pigs maintained acid-base homeostasis when diets contain limited additions of $NaHCO_3$ and $KHCO_3$. We speculate that magnitude of changes in dEB concentration were relatively small between the low and higher CP diets in our study, with limited effects to the acid-base balance, therefore, not eliciting growth or carcass performance differences.

Reduced performance observed in pigs fed the low CP diets with high supplemental crystalline AA was not influenced by dEB ranging from 48 to 107 mEq/kg indicating dEB is likely not the reason that pig performance is reduced when low CP diets are fed.

The effects of dietary supplementation of choline

Choline is involved in phospholipid synthesis, plays a role as an acetylcholine precursor, and can be oxidized to betaine in order to donate methyl groups. According to NRC (2012), the requirements for choline are 0.03% for finishing pigs. Although the levels of choline are well

above the NRC (2012) requirements in diets with low amounts of SBM, there is a 17% reduction in dietary choline when SBM content is reduced from 10.6 to 4.0%.

Russett et al. (1979) conducted a 35-d experiment to determine the effects of two choline levels (0 or 330 mg/kg) in conjunction with two levels of methionine (0.12 or 0.32%) in a 11% CP, semi-purified, corn starch-isolated soy protein diet on nursery pig growth performance. Main effects of choline and methionine were significant for ADG, but no interactions were observed. In addition, there were no differences in ADFI or G:F in pigs fed diets with supplemental choline. The authors concluded that added choline is required in an 11% CP, semi-purified diet when only 0.32% methionine is present. Conversely, the NCR-42 committee (NCR-42 committee, 1980) conducted a 47-d trial to evaluate the effects of supplemental choline (0, 86, 172, and 344 mg/kg) in corn-soybean meal based diets containing 11% CP on growth performance of finishing pigs. The addition of choline did not provide any benefit in ADG, ADFI, or G:F. Similarly, Smith et al. (1994) conducted a 48-d trial to evaluate the effects of supplemental choline (0 or 100 mg/kg) on growth and carcass performance of finishing gilts, and observed that G:F decreased in pigs fed diets with added choline. However, no differences were observed for ADG, ADFI, or carcass performance compared with the control treatment. Furthermore, Silijander-Rasi et al. (2003) conducted a 75-d trial to evaluate the effects of supplemental choline (578, 1,155, or 2,310 mg/kg) in 15% CP, corn-soybean meal based diets on growth and carcass performance of growing-finishing pigs, and reported no effects on growth or carcass performance. The results of our studies (Exp. 3 and 4) are consistent with the NRC-42 committee (1980), Smith et al. (1994), and Silijander-Rasi et al. (2003) whom observed no benefits to supplemental choline in finishing diets.

Dehulled soybean meal and corn contains 2,218 and 620 mg/kg of total choline with an estimated bioavailability of 83 and 100%, respectively (Emmert and Baker, 1997). Because corn-soybean meal diets have high levels of choline, finishing pigs have not shown responses to supplemental choline, even in low CP, AA fortified diets (NRC-42 committee, 1980). This was confirmed in our research as added choline did not alter performance of finishing pigs fed added choline.

The effects of dietary supplementation of K

Potassium is involved in electrolyte balance and neuromuscular function, and the Na-K pump physiological mechanism. According to the NRC (2012), the requirements for K are 0.17% for finishing pigs. Although the levels of K are well above the NRC (2012) requirements in diets with low amount of SBM, there is a 25% reduction in dietary K when SBM content is reduced from 10.6 to 4.0%.

According to Golz and Crenshaw (1990) dietary K concentrations ranging from deficiency to levels in excess may alter swine growth performance. In addition, they suggested interactions between K and Cl, and reported maximum response for ADG and G:F was obtained at 0.60 and 0.30% for K and Cl, respectively, in nursery pigs fed purified diets. Golz and Crenshaw (1991) suggested that K × Cl interaction reported previously (Golz and Crenshaw, 1990) was not due to a direct interaction between ions, but related to changes in excretion and retention of additional ions involved in N metabolism, and most likely responsible for changes in growth. Similarly, Miyada and Cline (1983) suggested that K supplementation increased ADG in nursery pigs fed low Lys diets (0.75%) by 21.6% compared with only 1.8% for those fed high

Lys diets (1.00%). Conversely, Brumm and Schricker (1989) evaluated the effects of increasing dietary K in corn-soybean meal-based diets containing 13% CP on growing-finishing pigs, and reported no effects on growth or carcass performance. Furthermore, Kephart and Sherritt (1990) evaluated the effects of added K in corn-soybean meal diets containing 11% CP on growing pigs, and reported no effects on growth performance. Similarly, O'Quinn et al. (2000) fed supplemental K (0 or 2%) in corn-soybean meal based diets containing 15% CP 7-d before slaughter to 114 kg pigs, and reported no effects on growth or carcass performance. The findings of Brumm and Schricker (1989), Kephart and Sherritt (1990), and O'Quinn et al. (2000) are consistent with the results of Exp. 3, where K supplementation had no effects on growth or carcass performance.

Brumm and Schricker (1989) suggested that no response to supplemental dietary K was observed because corn-soybean meal-based diets contain sufficient K to meet the pig requirements. According to NRC (2012), soybean meal contains 2.24% K, and it is estimated to be 97% bioavailable. In addition, corn contains 0.32% K, with 90 to 95% of bioavailability. The high level of bioavailability found in corn and soybean meal lend further confidence that concern for K in swine fed corn-soybean meal based diets is of little practical consequence (Combs and Miller, 1995). Our data extend this conclusion to heavier finishing pigs fed diets containing low CP.

In conclusion, the results of these experiments suggest that dietary SBM concentration is important to prevent decreased growth performance in finishing pigs fed low CP diets. Furthermore, it may suggest that one or more biologically active compounds found within SBM may be contributing to the responses observed. However, adding supplemental choline or K or balancing diets for dEB are not effective methods to restore performance in low SBM containing

diets in diets for finishing pigs above 100 kg. Further research is needed to understand the reasons why pigs fed diets with seemingly adequate levels of AA, but with less than 10.6% SBM, have decreased growth performance.

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TABLES

Table 4.1. Diet composition in Exp. 1 (as-fed basis)[1]

	CP, %					
	10	12				
Item Soybean meal, %	4.0	10.6	7.7	4.9	2.7	0.0
Ingredient, %						
Corn	91.76	84.89	86.14	87.30	88.23	89.31
Soybean meal (46.5% CP)	4.00	10.63	7.67	4.88	2.69	0.01
Corn gluten meal	---	---	1.81	3.63	5.00	6.70
Choice white grease	1.35	2.25	2.00	1.70	1.48	1.25
Monocalcium P (21% P)	0.56	0.52	0.54	0.56	0.58	0.60
Limestone	1.05	0.98	1.00	1.03	1.05	1.08
Salt	0.35	0.35	0.35	0.35	0.35	0.35
L-Lys-HCl	0.33	0.13	0.20	0.27	0.33	0.39
DL-Met	0.11	0.06	0.04	0.03	0.02	---
L-Thr	0.10	0.01	0.02	0.03	0.04	0.04
L-Trp	0.04	0.00	0.02	0.03	0.04	0.05
L-Val	0.06	---	---	---	---	---
L-Ileu	0.11	---	0.01	0.02	0.03	0.04
Trace mineral premix[2]	0.10	0.10	0.10	0.10	0.10	0.10
Vitamin premix[3]	0.08	0.08	0.08	0.08	0.08	0.08
Phytase[4]	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) AA, %						
Lys	0.55	0.55	0.55	0.55	0.55	0.55
Ile:Lys	75	75	75	75	75	75
Leu:Lys	164	191	209	228	242	259
Met:Lys	51	47	46	46	46	45
Met & Cys:Lys	86	86	86	86	86	86
Thr:Lys	67	67	67	67	67	67
Trp:Lys	20.5	20.5	20.5	20.5	20.5	20.5
Val:Lys	80	88	87	86	86	85
His:Lys	40	50	48	47	45	44
SID Lys:NE, g/Mcal	2.07	2.07	2.07	2.07	2.07	2.07
NE NRC, kcal/kg	2,659	2,659	2,659	2,659	2,659	2,659
CP, %	10.0	12.0	12.0	12.0	12.0	12.0
Ca, %	0.53	0.53	0.53	0.53	0.53	0.53
P, %	0.41	0.43	0.43	0.42	0.41	0.41
Available P, %	0.26	0.26	0.26	0.26	0.26	0.26
Standardized digestible P, %	0.29	0.30	0.30	0.29	0.29	0.29

[1]Diets were fed from d 0 to 23 which correspond to 114.2 to 135.6 kg BW, respectively.

[2]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[3]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[4]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 401 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 4.2. Diet composition in Exp. 2 (as-fed basis)[1]

	CP, %			
	10		13	
Item dEB, mEq/kg:	48	107	48	107
Ingredient, %				
Corn	92.64	91.82	82.77	83.00
Soybean meal, (46.5% CP)	3.29	3.35	12.51	12.49
Choice white grease	0.55	0.80	2.00	1.90
Monocalcium P, (21% P)	0.50	0.50	0.45	0.45
Limestone	1.35	1.35	0.98	1.30
Salt	0.35	0.35	0.35	0.35
L-Lys-HCl	0.51	0.51	0.23	0.23
DL-Met	0.08	0.08	0.03	0.03
L-Thr	0.19	0.19	0.06	0.06
L-Trp	0.06	0.06	0.01	0.01
L-Val	0.15	0.15	---	---
L-Ile	0.15	0.15	---	---
Trace mineral premix[2]	0.10	0.10	0.10	0.10
Vitamin premix[3]	0.08	0.08	0.08	0.08
Phytase[4]	0.02	0.02	0.02	0.02
Calcium chloride	---	---	0.43	---
Sodium bicarbonate	---	0.51	---	---
Total	100	100	100	100
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	0.66	0.66	0.66	0.66
Ile:Lys	64	64	65	65
Leu:Lys	133	132	165	165
Met:Lys	36	36	34	34
Met & Cys:Lys	60	60	64	64
Thr:Lys	66	67	66	66
Trp:Lys	19	19	19	19
Val:Lys	75	75	76	76
SID Lys: NE, g/Mcal	2.51	2.51	2.51	2.51
NE, kcal/kg	2,626	2,626	2,626	2,626
CP, %	10.1	10.1	13.1	13.1
Ca, %	0.61	0.61	0.61	0.61
P, %	0.37	0.37	0.40	0.40
Available P, %	0.25	0.25	0.25	0.25
Standardized digestible P, %	0.28	0.28	0.29	0.29

[1]Diets were fed from d 0 to 20 which correspond to 109.6 to 124.8.6 kg BW, respectively.

[2]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[3]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[4]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 401 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 4.3. Diet composition in Exp. 3 (as-fed basis)[1]

	CP, %			
	12	10		
Item	PC	NC	Choline[2]	Potassium[3]
Ingredient, %				
Corn	84.89	91.76	91.73	91.40
Soybean meal (46.5% CP)	10.63	4.00	4.01	4.03
Choice white grease	2.25	1.35	1.35	1.45
Monocalcium P (21% P)	0.52	0.56	0.56	0.56
Limestone	0.98	1.05	1.05	1.05
Salt	0.35	0.35	0.35	0.35
L-Lys-HCl	0.13	0.33	0.33	0.33
DL-Met	0.06	0.11	0.11	0.11
L-Thr	0.01	0.10	0.10	0.10
L-Trp	0.01	0.04	0.04	0.04
L-Val	---	0.06	0.06	0.06
L-Ile	---	0.11	0.11	0.11
Choline chloride 60%	---	---	0.03	---
Potassium chloride	---	---	---	0.24
Vitamin and trace mineral premix[4,5]	0.18	0.18	0.18	0.18
Phytase[6]	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	0.55	0.55	0.55	0.55
Ile:Lys	75	75	75	75
Leu:Lys	191	164	164	164
Met:Lys	47	51	51	51
Met & Cys:Lys	86	86	86	86
Thr:Lys	67	67	67	67
Trp:Lys	21	21	21	21
Val:Lys	88	80	80	80
SID Lys: NE, g/Mcal	2.07	2.07	2.07	2.07
NE NRC, kcal/kg	2,659	2,659	2,659	2,659
CP, %	12.0	10.0	10.0	10.0
Ca, %	0.53	0.53	0.53	0.53
P, %	0.43	0.41	0.41	0.41
Available P, %	0.26	0.26	0.26	0.26
Standardized digestible P, %	0.30	0.29	0.29	0.29
Choline, mg/kg	816	677	816	677

[1]Diets were fed from d 0 to 26 which correspond to 112.2 to 133.8 kg BW, respectively.
[2]Choline: choline supplemented diet (0.03% choline chloride).

[3]Potassium: potassium supplemented diet (0.24% potassium chloride).

[4]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[5]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[6]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 401 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 4.4. Diet composition in Exp. 4 (as-fed basis)[1]

	CP, %			
	12		10	
Item Added choline chloride [2], %	0	0.20	0	0.23
Ingredient, %				
Corn	84.89	84.51	91.76	91.41
Soybean meal (46.5% CP)	10.63	10.66	4.00	4.03
Choice white grease	2.25	2.40	1.35	1.45
Monocalcium P (21% P)	0.52	0.52	0.56	0.56
Limestone	0.98	0.98	1.05	1.05
Salt	0.35	0.35	0.35	0.35
L-Lys-HCl	0.13	0.13	0.33	0.33
DL-Met	0.06	0.06	0.11	0.11
L-Thr	0.01	0.01	0.10	0.10
L-Trp	0.00	0.00	0.04	0.04
L-Val	---	---	0.06	0.06
L-Ile	---	---	0.11	0.11
Trace mineral premix[3]	0.10	0.10	0.10	0.10
Vitamin premix[4]	0.08	0.08	0.08	0.08
Choline chloride 60%	---	0.20	---	0.23
Phytase[5]	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	0.55	0.55	0.55	0.55
Ile:Lys	75	75	75	75
Leu:Lys	191	191	164	164
Met:Lys	47	47	51	51
Met & Cys:Lys	86	85	85	85
Thr:Lys	67	67	67	67
Trp:Lys	20.5	20.5	20.5	20.5
Val:Lys	88	88	80	80
His:Lys	50	50	40	40
SID Lys:NE, g/Mcal	2.07	2.07	2.07	2.07
NE NRC, kcal/kg	2,659	2,659	2,659	2,659
Ca, %	0.53	0.53	0.53	0.53
P, %	0.43	0.43	0.43	0.43
Available P, %	0.26	0.26	0.26	0.26
Standardized digestible P, %	0.30	0.30	0.30	0.30
Choline, mg/kg	816	1,814	679	1,814

[1]Diets were fed from d 0 to 19 which correspond to 110.5 to 122.7 kg BW, respectively.
[2]Choline: supplementation with choline chloride to provide 1,814 mg of choline per kg of diet.

[3]Provided per kilogram of premix: 11 g Cu from copper sulfate, 0.2 g I from Ca iodate, 73 g Fe from ferrous sulfate, 22 g Mn from manganese sulfate, 0.2 g Se from sodium selenite, 73 g Zn from zinc sulfate.

[4]Provided per kilogram of premix: 3,527,360 IU Vitamin A, 881,840 IU vitamin D3, 17,637 IU vitamin E, 15 mg vitamin B12, 3,307 mg riboflavin, 33,069 mg niacin, 11,023 mg pantothenic acid, 1,764 mg menadione.

[5]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany, NJ). Provided 401 phytase units (FYT) per kg of diet with a release of 0.10% available P.

Table 4.5. Chemical analysis of experimental diets in Exp. 1 (as-fed basis)[1]

	CP, %					
	10	12				
Soybean meal, %	4.0	10.6	7.7	4.9	2.7	0.0
Proximate analysis, %						
DM	86.6	86.5	86.4	86.7	86.6	86.6
CP	10.3	13.0	11.9	12.4	11.7	12.4
Ca	0.64	0.67	0.80	0.70	0.69	0.66
P	0.40	0.45	0.43	0.41	0.43	0.40
Ether extract	3.7	4.3	4.1	4.1	3.8	3.9
Ash	3.6	4.6	4.6	3.9	4.0	3.7
Amino acids, %						
Lys	0.60	0.63	0.62	0.61	0.60	0.57
Ile	0.47	0.52	0.49	0.48	0.49	0.46
Leu	1.09	1.24	1.33	1.39	1.46	1.51
Met	0.28	0.26	0.26	0.26	0.26	0.26
Met & Cys	0.50	0.50	0.50	0.51	0.50	0.50
Thr	0.45	0.46	0.43	0.44	0.42	0.43
Trp	0.10	0.14	0.12	0.11	0.11	0.11
Val	0.54	0.61	0.58	0.56	0.58	0.55
His	0.24	0.31	0.29	0.28	0.28	0.26
Phe	0.51	0.64	0.63	0.63	0.64	0.64

[1]Diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of the trial and 3 d prior to the end of the trial and stored at -20°C, then amino acid analysis was conducted on composite samples by Ajinomoto Heartland, Inc. (Chicago, IL). Samples of the diets were also submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM, CP, Ca, P, ether extract, and ash.

Table 4.6. Chemical analysis of experimental diets in Exp. 2 (as-fed basis)[1]

	CP, %			
	10		13	
dEB, mEq/kg:	48	107	48	107
Item				
DM, %	87.7	86.9	87.5	87.5
CP, %	9.8	9.2	11.9	12.6
Ca, %	0.60	0.75	0.63	0.63
P, %	0.42	0.42	0.41	0.42
Na, %	0.12	0.33	0.17	0.14
Cl, %	0.36	0.42	0.56	0.30
K, %	0.44	0.41	0.55	0.54
Ether extract, %	4.1	3.9	4.8	4.5
Ash, %	2.41	3.07	3.07	2.97
Analyzed dEB, mEq/kg[2]	63	114	57	130

[1]Multiple diet samples were collected from each diet throughout the study, homogenized, then subsampled for analysis at Ward Laboratories, Inc. (Kearney, NE).

[2]dEB, mEq/kg=(Na%*434.98)+(K%*255.74)-(Cl%*282.06)

Table 4.7. Chemical analysis of experimental diets in Exp. 3 (as-fed basis)[1]

	CP, %			
	12	10		
	PC[2]	NC[3]	Choline[4]	Potassium[5]
Item				
DM, %	87.5	86.8	86.4	88.3
CP, %	12.7	10.3	10.3	10.5
Ca, %	0.67	0.75	0.68	0.66
P, %	0.38	0.38	0.35	0.38
Ether extract, %	4.7	4.7	4.1	4.0
Ash, %	3.3	2.8	4.2	4.4
K, %	0.55 (0.51)[6]	0.42 (0.39)	0.42 (0.39)	0.54 (0.51)
Choline, mg/kg	518 (816)	454 (677)	511 (816)	461 (677)

[1]Diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of the trial and 3 d prior to the end of the trial and stored at -20°C, until analysis. Samples of the diets were submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM, CP, Ca, P, ether extract, ash, and K. Samples of the diets were submitted to Barrow-Agee (Memphis, TN) for analysis of choline.

[2] NC: Negative control with 10% CP and 4.0% soybean meal.

[3] PC: Positive control with 12% CP and 10.6% soybean meal.

[4] Choline: choline supplemented diet (0.03% choline chloride).

[5]Potassium: potassium supplemented diet (0.24% potassium chloride).

[6]Values in parentheses indicate those calculated from diet formulation and are based on values from NRC, 2012 (Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington DC).

Table 4.8. Chemical analysis of experimental diets in Exp. 4 (as-fed basis)[1]

	CP, %			
	12		10	
Added choline[2], %	0	0.20	0	0.23
Item, %				
DM	87.6	87.3	87.4	87.2
CP	11.7	11.6	9.3	9.7
Ca	0.67	0.64	0.74	0.68
P	0.39	0.41	0.38	0.39
Ether extract	5.2	5.1	4.8	5.1
Ash	3.1	3.5	3.0	3.0

[1]Diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of the trial and 3 d prior to the end of the trial and stored at -20°C, until analysis. Samples of the diets were submitted to Cumberland Valley Analytical Service (Hagerstown, MD) for analysis of DM, CP, Ca, P, ether extract, and ash.

[2]Choline: supplementation with choline chloride to provide 1,814 mg of choline per kg of diet.

Table 4.9. Effects of decreasing soybean meal with 12% CP on growth performance of finishing pigs (Exp. 1)[1]

	CP, %									
	10	12						Probability, *P* <		
Soybean meal, %	4.0	10.6	7.7	4.9	2.7	0.0	SEM	NC[2] vs. PC[3]	Linear	Quadratic
Item										
Live weight, kg										
d 0	114.2	114.2	114.2	114.2	114.2	114.2	0.98	0.981	0.963	0.998
d 23	136.3	136.2	135.7	135.7	134.9	134.9	1.07	0.883	0.077	0.994
d 0 to 23										
ADG, kg	0.96	0.95	0.94	0.93	0.90	0.90	0.022	0.774	0.061	0.952
ADFI, kg	3.60	3.36	3.37	3.43	3.56	3.50	0.060	0.007	0.018	0.858
G:F	0.267	0.284	0.278	0.273	0.253	0.257	0.0070	0.062	0.001	0.930
Carcass characteristics										
HCW, kg	104.4	104.5	104.3	104.4	103.4	103.5	0.99	0.223	0.125	0.704
Carcass yield, %	76.5	76.8	76.6	76.6	76.2	76.5	0.42	0.556	0.387	0.717
Carcass ADG[5], kg	0.73	0.73	0.72	0.71	0.69	0.69	0.017	0.889	0.037	0.967
Carcass G:F[6]	0.204	0.218	0.213	0.209	0.193	0.197	0.0050	0.048	0.001	0.858

[1]A total of 280 pigs (DNA 600 × 241) were used with 7 or 8 pigs per pen and 6 replications per treatment.
[2] NC: Negative control with 10% CP and 4.0% soybean meal.
[3] PC: Positive control with 12% CP and 10.6% soybean meal.
[5]Carcass average daily gain = overall ADG × carcass yield.
[6]Carcass G/F = carcass average daily gain/average feed intake.

Table 4.10. Effects of dietary electrolyte balance and CP on growth performance and carcass characteristics, of finishing pigs (Exp. 2)[1,2]

	CP, %							
	10		13			Probability, *P* <		
dEB, mEq/Kg:	48	107	48	107	SEM	CP × dEB	CP	dEB
Live weight, kg								
d 0	110.5	110.4	110.4	110.4	0.57	0.178	0.699	0.247
d 20	124.3	123.9	125.0	125.9	0.71	0.291	0.037	0.657
d 0 to 20								
ADG, kg	0.72	0.71	0.77	0.81	0.021	0.236	0.001	0.442
ADFI, kg	2.83	2.77	2.75	2.89	0.063	0.083	0.730	0.451
G:F	0.254	0.256	0.279	0.280	0.0059	0.948	0.001	0.734
Carcass characteristics								
HCW, kg	95.2	95.1	95.3	96.2	0.66	0.420	0.329	0.511
Carcass yield, %	74.1	74.3	74.0	74.0	0.22	0.690	0.304	0.651
Carcass performance								
Carcass ADG[3], kg	0.53	0.53	0.57	0.60	0.015	0.263	0.002	0.386
Carcass G:F[4]	0.190	0.188	0.207	0.206	0.0045	0.898	0.001	0.709

[1]A total of 288 pigs (PIC 327 ×1050) were used in a 20-d experiment with 8 pigs per pen and 9 pens per treatment.

[2]Sodium bicarbonate was added to the diet with 10% CP to increase dEB to 107 mEq/kg. Calcium chloride was added to the diet with 13% CP to lower dEB to 48 mEq/kg.

[3]Carcass average daily gain = overall ADG × carcass yield.

[4]Carcass G/F = carcass average daily gain/average feed intake.

Table 4.11. Evaluation of dietary supplementation of choline chloride or potassium chloride in low CP diets on growth performance and carcass characteristics of finishing pigs (Exp. 3)[1]

	CP, %							
	12	10				Probability, *P*<		
	PC[2]	NC[3]	Choline[4]	K[5]	SEM	12 vs 10% CP[6]	Choline[7]	K[8]
Live weight, kg								
d 0	112.2	112.2	112.2	112.2	0.90	0.921	0.902	0.998
d 26	134.7	133.5	133.5	133.5	0.93	0.600	0.960	0.938
d 0 to 26								
ADG, kg	0.84	0.82	0.82	0.82	0.025	0.735	0.998	0.955
ADFI, kg	2.83	2.93	2.97	2.93	0.064	0.314	0.608	0.956
G:F	0.298	0.279	0.275	0.280	0.0052	0.085	0.548	0.918
Carcass characteristics[9]								
HCW, kg	101.0	100.7	99.3	99.9	1.01	0.101	0.254	0.489
Carcass yield, %	74.4	74.9	74.1	74.3	0.31	0.289	0.105	0.160
Backfat[10], mm.	18.4	17.3	17.5	17.3	0.75	0.840	0.861	0.933
Loin depth[10], mm.	56.1	56.3	56.9	57.8	1.89	0.929	0.730	0.454
Lean[10], %	52.0	52.3	52.7	52.4	0.52	0.896	0.887	0.601
Carcass performance								
Carcass ADG[11], kg	0.63	0.61	0.59	0.61	0.019	0.310	0.513	0.901
Carcass G:F[12]	0.222	0.209	0.202	0.208	0.0042	0.028	0.222	0.826

[1]A total of 284 pigs (DNA 600 × 241) were used in a 26-d experiment with 7 or 8 pigs per pen and 9 replications per treatment.

[2] NC: Negative control with 10% CP and 4.0% soybean meal.

[3] PC: Positive control with 12% CP and 10.6% soybean meal.

[4]Choline: choline supplemented diet (0.03% choline chloride).

[5]Potassium: potassium supplemented diet (0.24% potassium chloride).

[6] Contrast positive control diet compared to the three diets with 10% CP.

[7]Contrast negative control diet vs negative control supplemented with choline.

[8]Contrast negative control diet vs negative control supplemented with K.

[9]Recovery of carcass data from the processing plant was 65, 59, 49, and 65% for positive control, negative control, choline supplementation, and potassium supplementation treatment, respectively.

[10]Adjusted using HCW as a covariate.

[11]Carcass average daily gain = overall ADG × carcass yield.

[12]Carcass G/F = carcass average daily gain/average feed intake.

Table 4.12. Evaluation of supplementation of choline chloride in low CP diets on growth performance of finishing (Exp. 4)[1]

	CP, %							
	12		10			Probability, *P*<		
Added choline[2], %	0	0.20	0	0.23	SEM	CP × Choline	CP	Choline
Live weight, kg								
d 0	110.5	110.5	110.5	110.5	0.89	0.994	0.973	0.938
d 19	123.3	123.1	122.3	122.1	0.82	0.964	0.036	0.670
d 0 to 19								
ADG, kg	0.67	0.67	0.62	0.61	0.028	0.907	0.076	0.808
ADFI, kg	2.50	2.51	2.50	2.51	0.057	0.976	0.889	0.976
G:F	0.266	0.265	0.248	0.245	0.0081	0.772	0.020	0.891

[1]A total of 254 pigs (DNA 600 × 241) were used in a 19-d experiment with 7 or 8 pigs per pen and 8 replications per treatment.
[2]Choline: supplementation with choline chloride to provide 1,814 mg of choline per kg of diet.

Chapter 5 – Technical note: Regression analysis to predict the impact of dietary neutral detergent fiber on carcass yield in swine

ABSTRACT:

Research has shown that carcass yield in swine is reduced when feeding dried distillers grains with solubles (DDGS) or other ingredients with high NDF. Carcass yield reduction from feeding high-fiber ingredients results from an increase in the weight of intestinal contents, and the increase in gut fill is a result of the type of fiber in the ingredients. Neutral detergent fiber has been shown to result in the digestive contents to swell in the large intestine by absorbing water thus increasing the fecal volume in the large intestine. Considering the financial implications of changing carcass yield, the objective of this project was to develop a regression equation to estimate carcass yield from dietary NDF withdrawal strategies. Data from 8 trials (43 observations) originated from 5 journal articles, 2 theses and 1 technical memo were used to develop the regression equation. Treatment diets of each trial were reformulated to obtain dietary nutrient content using the NRC (2012) ingredient library. Composition of experimental diets was used to calculate dietary NE (kcal/kg), CP (%), crude fiber (CF [%]), NDF (%), and ADF (%) in the last two dietary phases. The PROC GLIMMIX procedure of SAS (SAS Institute, Inc., Cary, NC) was used to develop regression equations. The model was determined using a step-wise selection procedure starting with manual forward selection through individual predictor variables, with a statistical significance at $P < 0.05$ used to determine inclusion of terms in the final model. The resulting regression equation was carcass yield % = 0.03492 ± 0.02633 × WP (d) – 0.05092 ± 0.02862× NDF1 (%) – 0.06897 ± 0.02931 × NDF2 (%) – 0.00289 ± 0.00216 × (NDF2 (%) × WP (d)) + 76.0769 ± 1.33730. The regression analysis showed that number of days

in the withdrawal period (WP), NDF level in the dietary phase prior to the final phase (NDF1), NDF level in the last dietary phase before marketing (NDF2), and the interaction between NDF2 and WP (NDF2 × WP) were the most important variables in the dataset to predict carcass yield. As expected, high levels of NDF had a negative impact on carcass yield. Increasing the length of the withdrawal period improved carcass yield; however, the effect of withdrawal period was dependent on the level of NDF2, as indicated by the interaction term. In conclusion, the equations herein provides an estimation of the impact of dietary NDF on carcass yield.

Key words: carcass yield, mixed models, neutral detergent fiber, regression equations

INTRODUCTION

Multiple studies have investigated the impact of high fiber ingredients on swine growth and carcass characteristics. Reports have indicated that up to 30% distillers dried grains with solubles (DDGS) can be fed without compromising growth performance (De Decker et al., 2005; Stein and Shurson, 2009; Jacela, 2009). However, research has also shown that carcass yield is reduced when DDGS or other ingredients containing high concentrations of dietary NDF are fed (Linneen et al., 2008). High NDF increases weight of intestinal contents at harvest (Turlington, 1984; Anugwa, 1989). One successful strategy to ameliorate the negative effects on carcass yield is removing high NDF ingredients from the diet before harvest. Research has reported that pigs transitioned from a high NDF diet to a corn-soybean meal diet before harvest had similar carcass yield compared with pigs fed a corn-soybean meal diet during the entire finishing phase (Asmus et al., 2014; Graham et al., 2014; Coble et al., 2015). Because of the financial implications of improving carcass yield, the objective of this project was to develop prediction equations to

accurately estimate the change in carcass yield from dietary NDF and NDF withdrawal strategies.

MATERIALS AND METHODS

Meta-analysis

A literature review was conducted to compile studies that examined the effects of high insoluble fiber ingredients and withdrawal strategies on carcass yield. The literature search was conducted via the Kansas State University Libraries, utilizing the CABI search engine, and using the keywords “neutral detergent fiber”, “withdrawal strategies”, and “growing-finishing pigs”. Data was derived from both refereed and non-refereed publications including theses, technical memos, and university publications. The final database resulted in publications from 2007 to 2015.

Selection for inclusion and exclusion criteria

In order to be included in the final database, experiments had to meet the following criteria: 1) pigs used in experiments had ad libitum access to feed and water; 2) the percentage of dietary ingredients fed throughout the experiment was adequately defined; 3) experimental treatments included removal of high NDF ingredients, including a corn-soybean meal diets as control treatment and 4) the experiments provided information including duration of the feeding period, initial BW, final BW, ADG, ADFI, G:F, NDF from the last 2 dietary phases, duration of withdrawal period and carcass yield. The initial search yielded 8 publications. One paper was eliminated from the analysis because a control treatment was not used. The final database resulted in 7 papers and 8 different studies with a total of 43 treatment observations (Table 5.1).

Diet composition calculations

Treatment diets of each trial were reformulated using a spreadsheet-based software program (Kansas State University Diet Formulation Program V.8.1) to obtain dietary nutrient content based on values obtained from NRC ingredient library (Chapter 17, NRC, 2012). Composition of experimental diets was used to calculate dietary NE (kcal/kg), CP (%), crude fiber (CF [%]), NDF (%), and ADF (%) concentrations in the last two dietary phases as-fed basis and were recorded in the template for each dietary treatment. In addition, NDF withdrawal period in days as well as the standard error (SE) were collected for each treatment in all experiments.

Statistical analysis

The PROC GLIMMIX procedure of SAS (SAS Institute, Inc., Cary, NC) was used to develop regression equations to predict carcass yield for finishing pigs. The method of restricted maximum likelihood was used in the model selection to evaluate significance of fixed effect terms. The model was determined using a step-wise selection procedure starting with manual forward selection through individual predictor variables, with a statistical significance at $P < 0.05$ used to determine inclusion of terms in the model. Throughout the selection process, studentized residuals plots were observed to determine if quadratic or interaction terms needed to be tested in the model. Residual plots were also used to investigate outliers. For development of the statistical model, study was included as a random effect according to procedures suggested by St-Pierre (2001). In addition, observations were weighted across studies according to the within study pooled SE. To determine the weighting, the SE of each mean was inverted and squared, and subsequently divided by the original SE to express the results on the same scale as

the original data. Lastly, the WEIGHT statement in SAS provided a weight for each of these transformed values. Thus, observations with a smaller SE were weighted heavier, thus, having greater influence in the results than observations with larger SE.

RESULTS AND DISCUSSION

Prediction equation for carcass yield add the equation

The resulting regression equation was carcass yield %= 0.03492 ± 0.02633 × WP (d) – 0.05092 ± 0.02862× NDF1 (%) – 0.06897 ± 0.02931 × NDF2 (%) – 0.00289 ± 0.00216 × (NDF2 (%) × WP (d)) + 76.0769 ± 1.33730. The regression analysis revealed that the number of days in the withdrawal period (WP), NDF level in the dietary phase before the final phase (NDF1), NDF level in the withdrawal period before marketing (NDF2), and the interaction between NDF2 and WP (NDF2 × WP) were significant variables in the dataset to explain changes in carcass yield.

As expected, high NDF had a negative impact on carcass yield. Increasing the length of the withdrawal period improved carcass yield; however, the effect of withdrawal period was dependent on the level of NDF2, as indicated by the interaction term. According to Turlington (1984), the reduction in carcass yield from feeding high-fiber ingredients results from an increase in the weight of intestinal contents in the colon and cecum. The increase in gut fill is a result of the type of fiber in the ingredient. Neutral detergent fiber has been shown to result in the digestive contents to swell in the large intestine by absorbing water thus increasing the fecal volume in the large intestine (Coble et al., 2015).

Application of prediction equations

An example using this equation is presented in Figure 5.1. In the simulation, pigs were fed with moderate and high NDF1 diets (16 and 21% NDF; equivalent to 35 and 50% DDGS, respectively), and then transitioned to diets with either 9 or 13% NDF during the last dietary phase (NDF2) fed anywhere from 5 to 40 d before marketing. Predicted carcass yield when pigs are fed a corn-soybean meal (9% NDF) diet during both dietary phases was 75.0%. There is an estimated yield decrease of 0.84 and 1.44% when NDF was 16 and 21% during the last two dietary phases, respectively.

Partial carcass yield recovery is apparent when pigs are fed a 16 or 21% NDF diet and transitioned to a 9% NDF diet, depending on the length of the withdrawal period. However, the model predicted that yield is not continually improved when the diet in the last phase contains 13% NDF. In this situation, the entire benefit is found in the first 5 d of feeding the 13% NDF diet with no further improvement thereafter. The minimal withdrawal period where pigs were switched to a different diet in the experiments used to develop the equation was 5 d. Consequently, the equation should not be used to predict withdrawal times of less than 5 d.

In summary, fiber withdrawal strategies appear to recover carcass yield with the magnitude depending on the NDF level of the last two dietary phases as well as the fiber withdrawal length.

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TABLES AND FIGURES

Table 5.1. Summary of papers used in the regression analysis to predict carcass yield in finishing pigs

First author, year	Source[1]	NDF1[2], %	NDF2[3], %	WP[4], d	Initial BW, kg	Final BW, kg	Carcass yield, %
Asmus, 2014	J	8.79 - 20.18	8.82 - 20.21	0-47	41.0	120.6 - 122.8	71.6 - 73.2
Coble, 2015 (Exp. 1)	T	8.79 - 20.18	8.82 - 20.20	0-20	38.4	124.6 - 126.0	71.2 - 72.7
Coble, 2015 (Exp. 2)	T	8.76 - 20.17	8.79 - 20.29	0-24	44.5	128.3 - 132.5	74.3 - 75.4
Gaines, 2007	J	8.72 - 15.25	8.75 - 15.28	0-42	66.1	126.9 - 128.5	75.9 - 77.1
Graham, 2014	J	8.79 - 20.18	8.83 - 20.20	0-24	55.8	122.9 - 126.8	72.8 - 74.2
Jacela, 2009	M	8.53 - 15.00	8.43 - 14.90	0-41	39.0	118.6 - 121.5	75.1 - 75.9
Nemecheck, 2013	J	8.79 - 20.18	8.82 - 20.20	0-17	49.6	127.5 - 129.0	74.7 - 75.1
Xu, 2010	J	8.76 - 15.26	8.82 - 15.31	0-63	30.0	121.0 - 125.0	75.8 - 77.0

[1] Source type: J=Journal, T=Thesis, M=Technical memo.

[2] Range of NDF concentration in dietary phase before the final phase.

[3] Range of NDF concentration in final dietary phase before marketing.

[4] Range of withdrawal period.

Table 5.2. Regression equation to predict carcass yield from dietary NDF and withdrawal strategies[1]

Yield, %	= 0.03492 ± 0.02633 × WP (d) – 0.05092 ± 0.02862× NDF1 (%) – 0.06897 ± 0.02931 × NDF2 (%) – 0.00289 ± 0.00216 × (NDF2 (%) × WP (d)) + 76.0769 ± 1.33730

[1] Data from 8 trials were used as a database for the statistical analysis to develop the model.

NDF1 (%) = NDF concentration in dietary phase before final dietary phase.

NDF2 (%) = NDF concentration in final dietary phase before marketing.

WP (d) = Withdrawal period.

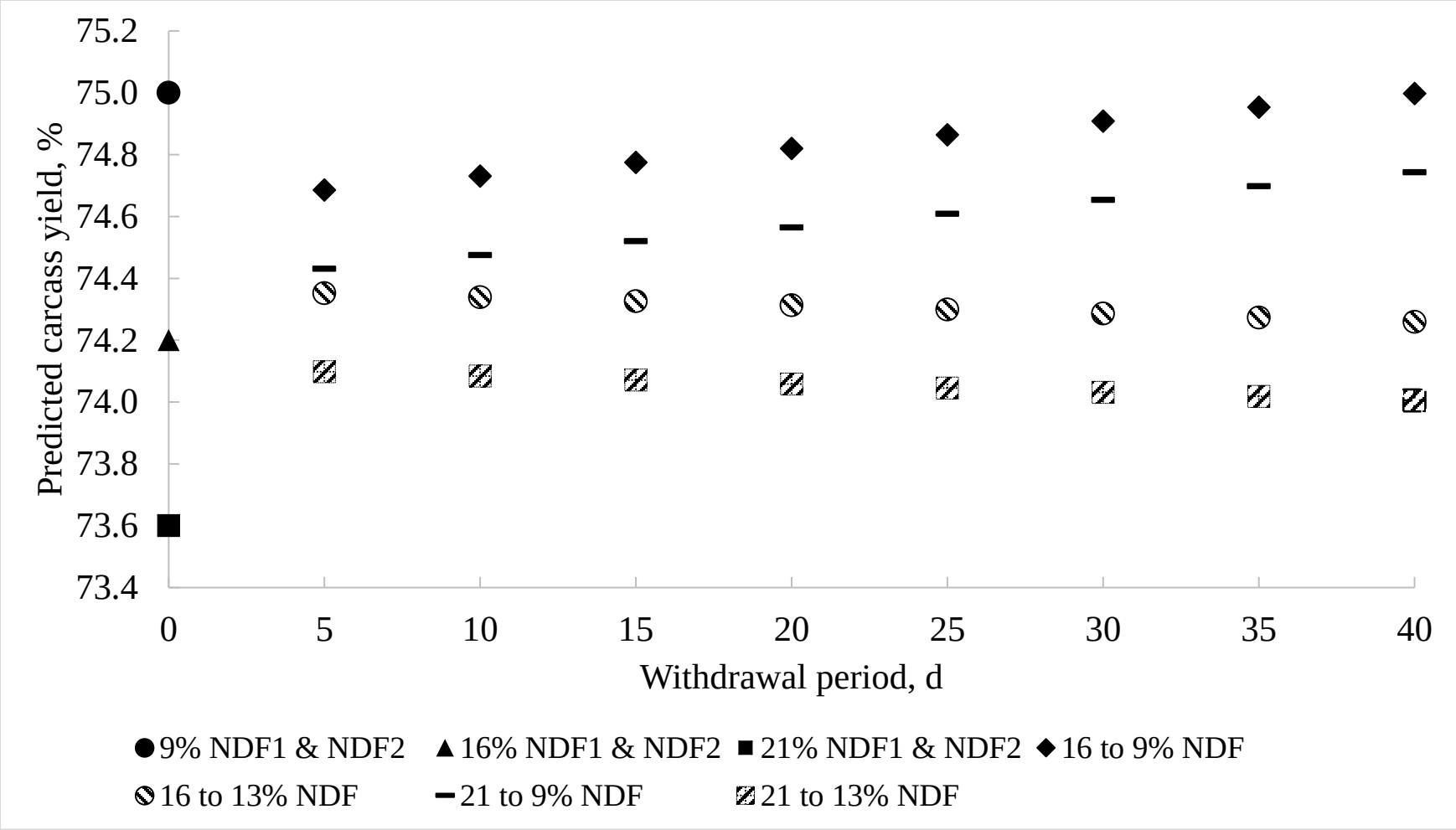

Figure 5.1. Predicted carcass yield of pigs fed varying NDF levels (9, 16, or 21%) in the last dietary phase before marketing (NDF2) and for pigs transitioned from a 21 or 16% NDF diet (NDF1) to a 9 or 13% NDF diet (NDF2).

Chapter 6 – Technical Note: Optimizing Dietary Net Energy for Maximum Profitability in Growing-Finishing Pigs

ABSTRACT

Knowledge of energy use by the pig is essential to predict, optimize, and formulate diets to achieve expected performance. Typically, the DE and ME systems have been used in the U.S.; however, the concentration of dietary NE provides a more accurate estimate of the amount of energy available to the pig. Taking into consideration the productive and financial implications of the energy density of the diet, the objective of this project was to develop a tool to estimate the dietary NE concentration that yields maximum profitability for growing-finishing pigs. A Microsoft Excel®-based model was developed to contrast dietary NE currently utilized by the user with recommended concentrations intended to maximize profitability in user-defined production and economic scenarios. The model is divided into 3 sections: 1) model inputs (including economics, production, and dietary criteria), 2) model calculations and optimization (including growth performance and carcass yield predictions, and profitability indicators), and 3) model outputs (including recommended dietary NE concentrations and profitability indicators). To calculate pig performance, the model uses prediction equations for ADG where ADG, g = 0.1135 × NE, kcal/kg + 8.8142 × Avg BW, kg - 0.05068 × (Avg BW, kg)^2 + 275.99, when Lys or other AA are not limiting (Nitikanchana et al., 2015). To calculate G:F, the assumption is that feed efficiency has a linear relationship with NE in the diet. Therefore, a 1% change in NE will result in a 1% change in feed efficiency. The model also uses the NDF content of the diet to estimate the effect of the diet on dressing percentage, where carcass yield (%) = 0.03492 × WP (d) – 0.05092 × NDF1 (%) – 0.06897 × NDF2 (%) – 0.00289 × NDF2 (%) × WP (d) + 76.0769.

For profitability calculations, a non-linear mathematical programming model was designed to select the optimum values of dietary NE that yield the maximum profitability for growing-finishing pigs. In this model, the objective function of income over total cost on a live- or carcass-basis is maximized by selecting the optimal value of NE in each dietary phase. The model described herein can be used to predict dietary NE content that yields the greatest economic benefit considering dynamic productive and economic scenarios.

Key words: growing-finishing pigs, linear programming, net energy

INTRODUCTION

Feed accounts for up to 75% of pork production cost, with energy alone representing 50% or more of the total cost (Noblet et al., 1993; Patience, 2009). The knowledge of energy utilization is essential to predict, optimize, and formulate diets to achieve expected performance. Typically, the DE (digestible energy) and the ME (metabolizable energy) systems have been the most common in the U.S. (Patience, 2009). However, the concentration of dietary NE provides the most accurate estimate of the amount of energy available to the pig (Noblet et al., 2007). Acknowledging the difficulties of measuring NE and limited availability of NE estimates for some dietary ingredients, Nitikanchana et al. (2015) developed and validated regression equations to predict growth rate and feed efficiency of growing-finishing pigs using the NE system. These equations provide a useful estimate for growth performance of pigs fed different dietary NE concentrations. Taking into consideration the financial implications of the energy density of the diet, the objective of this study was to develop a tool to estimate the dietary NE concentration that yields maximum profitability for growing-finishing pigs.

MATERIALS AND METHODS

Model description

The NE optimization tool is a Microsoft Excel®-based model. This tool is intended for use by swine nutritionists as a method to contrast current dietary NE concentrations to recommended values that yield maximum profitability. The model is divided into 3 sections: 1) model inputs, with economics, production, and dietary criteria; 2) model calculations and optimization for growth performance and carcass yield predictions, and profitability indicators, and 3) model outputs with recommended dietary NE concentrations, predicted growth performance, carcass yield, and profitability indicators contrasting current with the estimated ideal dietary NE concentrations.

User input page

Economics and system performance

For calculation of growth performance and profitability, the user is required to enter the following inputs: current ADG (g), G:F, and carcass yield (%), live price or pork carcass price ($/kg), feeder pig cost ($/pig), facility cost ($/pig/d), and other cost (i.e., veterinary supplies, insurance etc.; $/pig). For the growth curve, the user can utilize default values or input a custom growth curve. In addition, the profit determination criteria can be customized by selecting the economic evaluation based on a live- or carcass-basis and marketing pigs on either a fixed time or fixed weight basis.

Nutritional program specifics

In this section, the number of dietary phases is selected (currently the model allows to select from 4 to 6 phases) along with the BW range per phase. In addition, current, minimum, and maximum NE (kcal/kg) concentrations are specified by the user in each dietary phase. Inputs for minimum and maximum NE are set by the user to be the lowest and highest NE that can be practically achieved with available ingredients. With these three NE inputs, the model will calculate 5 equidistant NE values, maintaining the minimum, maximum as well as the current NE value used. Afterwards, the user needs to input the feed cost ($/t) for diets at each NE values in all phases and the percentage NDF associated to each concentration of dietary NE for diet phases 3 and greater.

Building the calculations for growth performance and economics

Growth performance prediction equations and SID Lys adequacy

This model utilizes the ADG prediction equations developed by Nitikanchana et al. (2015). Their publication provides two equations: 1) equation with adequate dietary SID Lys (this equation includes BW, dietary NE, and the quadratic term of BW as regressors) and 2) equation with dietary SID Lys at suboptimal values (this equation includes BW, dietary NE, and SID Lys). In the inputs section, the user is required to select if their diets are adequate in SID Lys or not. If diets are deficient, the user needs to input the SID Lys associated to each value of dietary NE in each dietary phase.

To calculate ADG, the user provides a current system overall ADG, which is partitioned to a current calculated ADG in each dietary phase with the use of a regression equation developed from a reference population (Table 6.1). Furthermore, ADG is calculated with the

inputs provided by the user (BW and dietary NE in each dietary phase). The difference between both, current and calculated ADG, are added or subtracted to predict ADG, which represents an adjustment to the intercept for the calculated ADG results.

To calculate G:F, the model utilizes estimations performed by Beaulieu et al. (2009), which suggested a 1:1 ratio between feed efficiency and dietary energy concentration. The model uses this ratio to calculate the influence of dietary NE on feed efficiency. Comparable to the procedures described to predict ADG, the user provides an overall feed efficiency, and these values are partitioned to a current feed efficiency (as G:F) in each dietary phase with the use of a growth curve from the reference population (Table 6.1).

Feed cost, SID Lys, and NDF prediction equations

For the calculated NE values not provided by the user, feed cost, SID Lys, and NDF for energy, are predicted using a set of regression equations that were developed using the least squares estimates method from the Linest function of Microsoft Excel. According to Briand and Carter (2011), the Linest function is an alternative to the use of least squares estimator formulas to obtain the best fit under a predefined criterion, and allows combinations with multiple functions to calculate statistics for other linear models.

For the feed cost prediction, Linest calculates the slope and intercept from the feed cost associated to each NE value provided by the user. In each dietary phase, a set of five linear regression equations are calculated by combining pairs of consecutive feed cost and associated NE values. The rationale supporting these calculations is to provide exact estimates of feed cost, and consequently more accurate economic estimates.

For the NDF prediction, Linest calculates a set of three linear regression equations (linear, quadratic, and cubic), and the equation with the best fit, is selected to estimate NDF. The regression equations are calculated by selecting the NDF and associated NE values in each dietary phase from the inputs provided by the user. The equation fit is determined by adjusted coefficient of determination, intended to account for the number of predictors in the model.

Comparable to the procedures to predict NDF, Linest calculates a set of three linear regression equations, and the model with the best fit is selected for estimation of SID Lys.

Regression equations to predict carcass yield

This model uses carcass yield prediction equations developed by Soto (2018) which provides an estimate of the effects of dietary NDF on carcass yield.

Building the linear programming model for optimization in Excel

A non-linear mathematical programming (NLP) model was designed to select the optimum values of dietary NE that yields the maximum profitability for growing-finishing pigs. In Microsoft Excel Solver, NLP problems are solved with the generalized reduced gradient (GRG) algorithm. In this model, the objective function is income over total cost (IOTC) on a live- or carcass-basis and is maximized by the optimal value of NE in each dietary phase.

Once economics, system performance, weight ranges, and dietary inputs are entered, the GRG algorithm begins the routine at any feasible solution (starting point). Then through multiple iterations across the feasible region, searches for a solution that provides the value of NE that satisfies the greatest profitability (IOTC) defined in the objective function. When no further possibility for profitability improvement exists, the current solution becomes local optima in

relation to nearby points. However, a global optimal solution represents the best possible solution for the objective function (Ragsdale, 2008). To land in the global optima, the model has the GRG in the Solver set up with the Multistart option, which selects several starting points throughout the feasible region, which produces multiple local optima solutions, which increases the chance of arriving to the global optima solution. The mathematical structure and economic calculations of the model are described in Tables 6.2 and 6.3.

RESULTS AND DISCUSSION

Application of the model

An example using this model is presented in Tables 6.4, 6.5, 6.6, and 6.7. In this example, a six-phase feeding program based on corn-soybean meal and dried distillers grains with solubles (DDGS) was used. To generate the NE range, a series of 5 diets per phase were formulated to include 0, 10, 20, 30, and 40% DDGS. In our simulation, the base feeding program used for comparisons had 20% DDGS added throughout all dietary phases. The resulting NE values from the 20% DDGS diets in this simulation were: 2,434, 2,474, 2,491, 2,524, 2,535, and 2,513 Kcal/kg for phases 1, 2, 3, 4, 5, and 6, respectively (Table 6.4). From phases 3 to 6, resulting NDF values had an average of 13% for diets with a 20% DDGS inclusion. The results of calculations for 5 equidistant NE values and respective NDF values are presented in Table 6.4.

For scenario building, the following inputs were used: 1) current overall ADG of 975 g; 2) current overall G:F of 0.345; 3) current carcass yield of 73.4%; 4) feeder pig cost of $55.00/pig; 5) facility cost of $0.11/pig/d; 6) other cost (veterinary supplies, field service personnel, trucking, etc.) of $8.00/pig.

Dynamic scenario variables definition

To further evaluate the model performance, DDGS pricing was modified from low-cost ($99.00/t) to high-priced ($165.00/t). Similarly, carcass pricing was also modified from moderate-priced ($1.43/kg) to high-priced ($1.87/kg). For calculation of feed cost the pricing of main ingredients used was: corn $0.137/kg ($3.48/bu), soybean meal $319.66/t, L-Lys $1.52/kg. Resulting feed costs are presented in Table 6.4.

Scenario results

Considering a scenario with low-priced DDGS and moderate carcass price, the model solution suggested that NE should be decreased, thus forcing in 40% DDGS. This decrease is only observed from phase 1 to 5. In phase 6, the model yielded no modification from the current energy value. The recommended NE values worsened ADG, feed efficiency, and carcass yield, nonetheless, the recommend NE values under the conditions of this scenario improved IOTC by $3.75/pig. Interestingly, by only changing the scenario to a high carcass price, the model solution suggested a similar NE decrease in phases 1 to 5 to the previously explained scenario. However, in phase 6 the model suggested the highest energy value, thus switching to a corn-soybean meal-based diet, thus improving carcass yield. With the use of the recommend NE values under the conditions of this scenario, IOTC improved by $3.76/pig over the current system performance.

Considering a scenario with high-priced DDGS and moderated carcass price, the model solution still suggested that NE should be decreased; however, the extent of this decrease is lower compared to the scenarios described above, particularly for phases 1 and 3. For phases 2 and 4, the recommend NE values remain the lowest, using the 40% DDGS diet. For phases 5 and 6, the recommended NE values are increased, particularly for phase 6. The recommended NE values slightly worsened feed efficiency, yet carcass yield was improved. With the use of the

recommend NE values under the conditions of this scenario, IOTC improved by $1.26/pig. With a more favorable scenario for carcass price, NE is moderately reduced for phases 1 and 3. For phase 2 the recommended NE value remained the lowest. For phase 4, the model yielded no modification, thus using the 20% DDGS diet. Like the previous scenario, the recommended NE values are increased for phases 5 and 6, particularly for phase 6. With the use of the recommend NE values under the conditions of this scenario, IOTC improved by $1.56/pig.

Potential drawbacks of model application

The prediction equations used in this model were developed from a determined database, thus the model should be used to predict growth or carcass performance within the range of nutrients in the database. Consequently, using the model when formulation is done with ingredients and nutrients outside the range used in the database should be done with caution.

The prediction equation for ADG in the model, indicates that for every 100 kcal/kg increase in dietary NE, an 11 g/d increase in ADG should be expected, which suggests that increasing dietary NE resulted in linear improvements in ADG at all BW ranges. De la Llata et al. (2001) reported that ADG linearly increased as energy density increased in growing pigs from 36 to 59 kg. Conversely, ADG was not affected in pigs from 59 to 120 kg, and suggested that pigs from 36 to 59 kg were in an energy-dependent phase. Conversely, increasing energy density did not improve ADG in pigs over 59 kg, suggesting that pigs were not in an energy-dependent phase. According to Campbell and Taverner (1988), the relationship between energy intake and protein deposition consist of an initial ascending linear component and a plateau representing the pig maximal rate of protein deposition, and addition of energy after maximal rate is incorporated

into body fat. If pigs achieve high feed intake, they may not respond to increasing energy density with a linear increase in ADG.

Whereas the impact of dietary fiber on dressing percentage is accounted for in the model, their impact is not properly considered for ADG, particularly for high fiber diets. To validate the regression equation for ADG, Nitikanchana et al., (2015) conducted two experiments including low, medium, and high-energy diets to compare actual and predicted ADG. In both experiments, small differences were observed between predicted and observed ADG except for the low-energy diet where the equation predicted a 4% greater than observed ADG in pigs fed diets containing 30% DDGS, 20% wheat middlings, and 4% soybean hulls. Factors such as bulkiness and limitation on intake (de Leeuw et al., 2008) or intestinal cell proliferation with a high energy requirement (Johnston et al., 2003) could lead to poor ADG, and may have explained the deviation from the predicted ADG. Thus, using the model with high fiber diets should be done with caution.

The experiments used for equation development were conducted with ad-libitum feeding regimen. Therefore, observed pig performance by changing NE while feed intake is restricted may be different than predicted by utilizing the prediction equations. Furthermore, experiments using intact males, immunocastrated males, or fed Ractopamine HCl were excluded from the databases (Nitikanchana et al., 2015; Soto, 2018). Thus, if potential interactions exist in the shape of the response curve to NE and Ractopamine HCl or NE and immunocastration, they are not contemplated in this model.

Summary

The model described herein can be used to predict the value of dietary NE that yields the greatest economic return to the production system. To evaluate the performance of the model, an example is presented considering different economic scenarios created by modifying DDGS and carcass pricing.

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TABLES

Table 6.1. Regression equation to partition ADG and G:F by dietary phase from overall growth performance inputs[1]

Growth performance	Model
ADG, g	= (0.0000000903 × Avg BW^3, kg – 0.0000794732 ×Avg BW^2, kg + 0.0196290876 × BW, kg + 0.8587771286) × 1000
G:F	= (0.0000001334 × Avg BW^3, kg – 0.0000746844 × Avg BW^2, kg + 0.0206218569× BW, kg + 0.9095818867) × 1000

[1] Growth curve reference taken from PIC 337 growing-finishing pigs (PIC internal data).

Table 6.2. General linear programming model

Objective function	Calculation
Income over total cost, live basis	
MAX (IOTC Live, $/pig):	*f(x)*= (∑ gain per phase, kg + Feeder pig BW, kg) × Live price, $/kg – Feed cost, $/pig + Facility cost, $/pig – Feeder pig cost, $/pig – Other costs
Subject to:	Phase 1 Predicted NE ≥ Minimum user NE, Phase 1 Predicted NE ≤ Maximum user NE
	Phase 2 Predicted NE ≥ Minimum user NE, Phase 2 Predicted NE ≤ Maximum user NE
	Phase 3 Predicted NE ≥ Minimum user NE, Phase 3 Predicted NE ≤ Maximum user NE
	Phase 4 Predicted NE ≥ Minimum user NE, Phase 4 Predicted NE ≤ Maximum user NE
	Phase n Predicted NE ≥ Minimum user NE, Phase n Predicted NE ≤ Maximum user NE
	Ph1 NE ≥ 0, Ph2 NE ≥ 0, Ph3 NE ≥ 0, Ph4 NE ≥ 0, Phn NE ≥ 0
Income over total cost, carcass basis	
MAX (IOTC Carcass, $/pig):	*f(x)*= ((∑ gain per phase, kg + Feeder pig BW, kg) × Carcass yield, $/kg) × Carcass price, $/kg – Feed cost, $/pig + Facility cost, $/pig – Feeder pig cost, $/pig – Other costs
Subject to:	Phase 1 Predicted NE ≥ Minimum user NE, Phase 1 Predicted NE ≤ Maximum user NE
	Phase 2 Predicted NE ≥ Minimum user NE, Phase 2 Predicted NE ≤ Maximum user NE
	Phase 3 Predicted NE ≥ Minimum user NE, Phase 3 Predicted NE ≤ Maximum user NE
	Phase 4 Predicted NE ≥ Minimum user NE, Phase 4 Predicted NE ≤ Maximum user NE
	Phase n Predicted NE ≥ Minimum user NE, Phase n Predicted NE ≤ Maximum user NE
	Ph1 NE ≥ 0, Ph2 NE ≥ 0, Ph3 NE ≥ 0, Ph4 NE ≥ 0, Phn NE ≥ 0

Table 6.3. Input equations used in model development

Indicator	Calculation
Predicted daily feed intake, g	= Calculated ADG, g/Calculated G:F
Phase duration[1], d (Fixed weight)	= (Targeted BW, kg – Initial BW, kg)/ (Calculated ADG, g/1000)
Total feed cost per phase, $/pig	= (Phase duration, d *(Predicted daily intake, g/d/1000) *(Diet cost, $/t/2000))
Gain per phase, kg	= Calculated ADG, g/1000*Phase duration
Feed cost per kg of gain, $/pig	= ((Total feed cost by phase, $/pig/ (Targeted BW, kg – Initial BW, kg)))
Total phase intake, kg/pig	= (Predicted daily intake, g/d/1000) * Phase duration, d
Feed and facility cost, $/pig	= Total feed cost, $/pig + (Phase duration, d*Facility cost, $/pig/d)
Income per pig live per phase, $/pig	= Gain per phase, kg * Live price, $/kg
IOFC[2] per phase, $/pig	= Income per phase, $/pig – Total feed cost per phase, $/pig
IOFFC[3] per phase, $/pig	= Income per phase, $/pig – Feed and facility cost, $/pig
Live aggregate gain, kg	= ∑ gain per phase, kg + Feeder pig BW, kg
Carcass aggregate gain, kg	= (∑ gain per phase, kg + Feeder pig BW, kg) * ((Inputted carcass yield, %)/100)
Total feed cost & facility cost, $/pig	= (∑ of feed cost per phase, $ + (∑ of phases duration, d * Facility cost, $/pig/d))
Gross income, $/pig (live basis)	= (∑ gain per phase, kg + Feeder pig BW, kg) * Live price, $/kg
Gross income, $ pig (carcass basis)	= (∑ gain per phase, kg + Feeder pig BW, kg) * ((Inputted carcass yield, %)/100) * Carcass price, $/kg
IOFFC live, $/pig	= ((∑ gain per phase, kg + Feeder pig BW, kg) * Live price, $/kg) – Total feed & facility cost, $/pig
IOFFC carcass, $/pig	= ((((∑ gain per phase, kg + Feeder pig BW, kg) * ((Predicted carcass yield, %)/100) * Carcass price, $/kg) – Total feed & facility cost, $/pig

[1]Calculation of phase duration for fixed time is based on user predicted duration in each phase
[2]Income over feed cost.
[3]Income over feed and facility cost.

Table 6.4. User inputs for minimum, current, maximum, and resulting NE levels in each dietary phase with their respective feed cost and neutral detergent fiber.

Dietary phase	NE[1], Kcal/kg	Feed cost[2,3], $/t		NDF[5], %
		Low-priced DDGS	High-priced DDGS	
1	2,388	175.68	202.08	---
	2,410	184.89	204.69	---
	2,434[4]	195.55	208.75	---
	2,452	206.61	213.21	---
	2,474	225.01	225.01	---
2	2,418	165.01	191.41	---
	2,440	174.87	194.67	---
	2,463[4]	185.27	198.47	---
	2,474	195.77	202.37	---
	2,507	215.04	215.04	---
3	2,447	154.94	181.34	17.4
	2,471	163.63	183.43	15.2
	2,491[4]	173.20	186.40	13.1
	2,518	184.91	191.51	10.9
	2,542	202.05	202.05	8.7
4	2,467	149.27	175.67	17.4
	2,491	158.52	178.32	15.3
	2,524[4]	167.95	181.15	13.1
	2,542	177.88	184.48	11.0
	2,566	195.78	195.78	8.8
5	2,482	144.96	171.36	17.4
	2,507	153.71	173.51	15.3
	2,535[4]	162.98	176.18	13.1
	2,555	172.79	179.39	11.0
	2,579	191.06	191.06	8.8
6	2,463	145.39	171.79	17.4
	2,487	152.81	172.61	15.3
	2,513[4]	160.72	173.92	13.1
	2,533	169.84	176.44	11.0
	2,555	180.18	180.18	8.8

[1]Model calculated 5 equidistant NE levels by phase, keeping minimum, maximum, and currently used NE levels as defined by the user.

[2]The feeding program had an inclusion of 20% dried distillers grains with solubles in all dietary phases.

[3]Main ingredients pricing: Corn $0.137/kg, Soybean meal $319.66/t, L-Lys $1.52/kg.

[4]Current levels of NE defined by user.

[5]Neutral detergent fiber defined by user for dietary phase 3 and greater.

Table 6.5. Recommended net energy levels (kcal/kg) compared with user defined levels in a six-phase feeding program with varying scenarios for distillers dried grains with solubles and carcass pricing on a fixed time marketing basis[1,2,3]

	DDGS, $/t:	99						165					
	Carcass, $/kg:	1.43			1.87			1.43			1.87		
Phase	BW, kg	Current[4]	Recom.[5]	Diff[6]., %	Current	Recom.	Diff., %	Current	Recom.	Diff., %	Current	Recom.	Diff., %
1	23 to 34	2.434	2,388	(1.9)	2.434	2,388	(1.9)	2.434	2,410	(1.0)	2.434	2,410	(1.0)
2	34 to 57	2,474	2,418	(2.3)	2,474	2,418	(2.3)	2,474	2,418	(2.3)	2,474	2,418	(2.3)
3	57 to 79	2,491	2,447	(1.8)	2,491	2,447	(1.8)	2,491	2,471	(0.8)	2,491	2,471	(0.8)
4	79 to 95	2,524	2,467	(2.3)	2,524	2,467	(2.3)	2,524	2,467	(2.3)	2,524	2,524	0.0
5	95 to 113	2,535	2,482	(2.1)	2,535	2,482	(2.1)	2,535	2,555	0.8	2,535	2,555	0.8
6	113 to 129	2,513	2,513	0.0	2,513	2,555	1.6	2,513	2,555	1.6	2,513	2,555	1.6

[1]A corn-soybean meal-dried distillers grains with solubles-based feeding program with six dietary phases was used for comparisons.
[2]The feeding program had an inclusion of 20% dried distillers grains with solubles in all dietary phases.
[3]Main ingredients pricing: Corn $0.137/kg, Soybean meal $319.66/t, L-Lys $1.52/kg.
[4]Current: user defined net energy levels by dietary phase.
[5]Recommended: optimized net energy levels by dietary phase.
[6]Difference between current and recommended energy levels expressed in percentage.

Table 6.6. Overall performance and economics of user defined net energy levels with recommended net energy levels compared with user defined levels in a six-phase feeding program with varying scenarios for distillers dried grains with solubles and carcass pricing on a fixed time marketing basis[1,2,3,4,5]

DDGS, $/t:	99				165			
Carcass, $/kg:	1.43		1.57		1.43		1.57	
Item	Current[4]	Recom.[5]	Current	Recom.	Current	Recom.	Current	Recom.
ADG, g	975	971	975	971	975	975	975	975
G:F	0.345	0.339	0.345	0.340	0.345	0.342	0.345	0.344
ADFI, g	2,830	2,862	2,830	2,858	2,830	2,839	2,830	2,830
Carcass yield, %	73.4	73.2	73.4	73.7	73.4	74.0	73.4	74.0
Phases duration, d	108.0	108.0	108.0	108.0	108.0	108.0	108.0	108.0
Total feed, kg/pig	305.0	308.9	305.0	308.2	305.0	306.4	305.0	305.5
Total feed cost, $/pig	53.01	48.37	53.01	49.38	56.69	56.36	56.69	56.50
Total feed cost & facility cost, $/pig	64.89	60.25	64.89	61.25	68.57	68.24	68.57	68.38
Gross Income, $/pig	135.97	135.46	177.81	177.24	135.97	135.78	177.81	177.71
Total IOFC[6], $/pig	82.97	87.08	124.80	127.87	79.29	79.42	121.12	121.22
Total, IOFFC[7] Carcass, $/pig	71.09	74.84	112.93	116.68	67.41	68.67	109.25	110.81
IOTC Carcass, $/pig	8.09	11.84	49.93	53.68	4.41	5.67	46.25	47.81

[1]A corn-soybean meal-dried distillers grains with solubles-based feeding program with six dietary phases was used for comparisons.
[2]The feeding program had an inclusion of 20% dried distillers grains with solubles in all dietary phases.
[3]Current: user defined net energy levels by dietary phase.
[4]Recommended: optimized net energy levels by dietary phase.
[5]Main ingredients pricing: Corn $0.137/kg, Soybean meal $319.66/t, L-Lys $0.31/kg.
[6]Income over feed cost.
[7]Income over feed and facility cost.

Appendix - Alternatives to antibiotics for livestock species

SUMMARY

Bacteria continue to become less susceptible to antimicrobial drugs over time, and rates of discovery for new antibiotics are decreasing[1,2,3]. Thus, intensive amount of research has been focused on the development of alternatives to antibiotics in the livestock industry[3,4]. Currently, several of these alternatives have been evaluated, giving promising but sometimes contrasting results[4,5,6]. This fact sheet will briefly some of the current alternatives available, including: acidifiers, antimicrobial peptides, copper, phytogenics, plasmid vaccination, probiotics, specialized proteins, yeast derivatives, zinc, and antibacterial vaccines.

Acidifiers

Acidifiers have been used for decades, mostly for feed preservation. Acidifiers can be classified as organic acids and their salts, inorganic acids, and blends of acids and salts[7]. Most commonly used acidifiers are formic, propionic, acetic, citric, benzoic or fumaric acid[8]. Organic and inorganic acid combinations are often used commercially[7], and products with mixed acids are reported to have increased performance compared to single acids due to synergistic effects[9]. In addition, some commercially available products contain acids coated with lipids and other molecules[7,10], mainly to protect and release the acid in the targeted location to ultimately improve their effectiveness[10]. Several modes of action have been suggested for acidifiers: (1) reduction of diet pH, (2) antimicrobial effects by disruption of bacterial protein synthesis, (3) disruption of cell membrane integrity in bacterial pathogens, and finally (4) improvement of nutrient digestibility, mainly crude protein and dry matter[7,8,11]. Acidifiers have been shown to improve weight gain and feed efficiency in pigs[7,8,12] and poultry[11,12,13]. In pigs, the use of

acidifiers seems to be more beneficial the first weeks after weaning[7,12,14]. However, reported improvements in growth performance are highly dependent on dose, combination and nature of acidifiers[7], as well as diet composition[15].

Antimicrobial peptides

Antimicrobial peptides (AMPs) are small protein molecules produced and extracted from invertebrates, plants and animals[16]. Antimicrobial peptides serve as an important component of the host immune system with direct antimicrobial functions, targeting gram-positive and gram-negative bacteria, fungi, viruses, and other pathogens[4,17]. Antimicrobial peptides amino acid composition, positive charge, and three-dimensional structure allows for strong interactions with bacterial cell membranes[18]. These interactions are proposed to cause loss of membrane function, leakage of metabolites and ions and alteration of membrane permeability[4]. The exact nature of the mechanism of action of APMs remains unclear[19]. However, is it broadly accepted that AMPs antimicrobial activity resides on their bacterial cell membrane integrity disruption capabilities and by inhibiting protein synthesis[19]. In addition to their antimicrobial function, it is well documented that AMPs alter the host immune response, inducing the humoral immune system (which primarily produces antibodies) and cell-mediated immune system (involves deactivation of phagocytes and antigen-specific responses)[4,20]. Currently, the most prevalent use of AMPs has been in the preservation of food[9]. However, dietary supplementation of synthetic AMPs in swine[16] and broilers[20] has suggested improvements in cellular immune function. Although there is limited research on AMPs in animal models, their use seems promising[20].

Copper

Copper is a trace mineral required for the function of several enzymes and hemoglobin synthesis [21,22,23]. To meet livestock requirements, dietary Cu levels of 5 to 10, 6 to 8, and 10 ppm are

enough to meet swine[22], poultry[25], and beef cattle[26] requirements, respectively. However, Cu supplied at higher concentrations of 100 to 250 ppm in swine[24] and 125 to 250 ppm, in poultry[25,27] is known to stimulate growth performance, with no apparent benefits of higher concentration in beef cattle[28]. Supplemental Cu, fed conventionally as copper sulfate or tribasic copper chloride[22,25], improves feed intake, growth and feed conversion in weanling pigs[29,30], growing finishing pigs[31], and poultry[25,27]. Nevertheless, little information is known about the growth stimulation mechanisms[24,25]. Some of the possible mechanisms could be attributed to: (1) disruption of bacterial cell membranes where ions of Cu penetrate the cell membrane, altering the permeability and causing ion leakage, (2) lipid oxidation where ions of Cu enter the cell, stimulate lipid oxidation and combine with intracellular amino acids, which leads to protein denaturation and cell death, and (3) bacterial cell toxicity at higher Cu concentration[25]. Precaution must be taken when feeding high concentrations of Cu to swine as toxicosis has occurred by supplementing Cu above 250 ppm[22]. Also, it is important to consider that Cu excretion is directly proportional to Cu intake[24].

Phytogenics (Phytobiotics or botanicals)

Phytogenic feed additives are plant-derived products. While the exact mode of action and physiological effect of plant extracts are not fully understood, most are associated with antimicrobial benefits, increased antioxidant activity, and improved gut function[6]. Additionally, phytogenics can potentially increase diet palatability, which could lead to higher feed intake and growth rates[32,33]. Within the phytogenics classification, the active substances found in the products may vary widely depending upon the plant species, plant part used, harvesting season, and geographical origin. Plant extracts have been predominantly provided through essential oils. Essentials oils, are typically mixtures of secondary plant metabolites and may contain phenolic

compounds, terpenes, alkaloids, lectins, aldehydes, polypeptides[4]. The exact mode of action of essential oils has not been established, but the activity may be related to the potential of the hydrophobic essential oils to intrude into the bacterial cell membrane, disintegrate membrane structures, and cause ion leakage[32]. Furthermore, quorum sensing inhibition has been suggested as another mode of action for essentials oils and plant extracts and it will be reviewed in more detail.

Quorum sensing (QS): is a common bacterial cell to cell communication system[35,36] and allows bacteria to make collective decisions and act as a community[37]. This communication system involves the production, dissemination, and reception of signal molecules[38]. The concentrations of these substances reflect the density of bacterial cells in a defined environment[39]. When these concentrations reach a certain threshold in the surroundings, actions that involve the whole bacterial population are triggered[38]. As a result, the community is able to adapt behaviors that are advantageous for their survival[37]. A few examples of processes controlled by QS include: sporulation, biofilm formation, antibiotic production, and virulence adaptation[39]. The inhibition of the QS system has been broadly discussed as a way of combating bacterial infections or antibiotic resistant bacterial pathogens[7]. The QS inhibitors target the signal molecules by interfering with the signal generation, dissemination, or reception[40]. Therefore, QS inhibitors have no direct impact on bacterial growth, but reduce their pathogenicity, thus increasing the susceptibility of the pathogens to the host defenses[34]. In nature, QS inhibitor molecules have been found mainly in plant extracts (e.g. exudates from pea, erucin, garlic, *Vanilla planifora*, *Rosemarinus officinalis*, orange) and essentials oils (e.g. tea tree, rosemary, *Lippia alba*, *Piper bredemeyeri)*, but also have been found in fungi (e.g. *ganoderna lucidum*) and algae (e.g. furanones)[40,41]. Commercially, plant extracts and essentials oils are found in phytogenic

products, although the active substances can vary widely and the mode of action of these products has not been clearly established[4]. Overall, limited research has validated the potential benefits of phytogenics or the results have been inconclusive.

Plasmid vaccination

Pharmaceutical plasmids have become an indispensable molecular tool for the biotechnology industry by supporting the production of proteins, antibodies and vaccines[42]. Furthermore, plasmids are useful means of transportation for medically important genes, because of their capabilities to deliver and express genes[42], while avoiding defense barriers of the host organism[12]. Vaccination with plasmids involves the intramuscular or subcutaneous injection of DNA plasmid that contains a gene which is able to induce the humoral immune system (which primarily produces antibodies) and cell-mediated immune system (involves de activation of phagocytes and antigen-specific responses) to battle against specific pathogens[44,45]. Consequently, their use has been shown to be equivalent to traditional vaccines[43]. Their mode of action can be divided in five categories: (1) increased expression of endogenous proteins, (2) restoring normal levels of a protein as a consequence of disease, (3) specific antibody production against disease, (4) cytotoxicity, by introducing new functions to the cells, that contribute to killing invasive cells, and (5) blocking the formation of disease-related genes[42,43]. Interventions with plasmids vaccination have been successful within poultry[46], swine[47] and cattle[45], but this testing has been limited mainly to viral infections. Plasmid vaccination technology has proven to be effective in several animal models, although just a limited amount of vaccines have been tested[44] and improvement to the original formulations must be achieved[45].

Probiotics

Probiotics are live cultures of defined microorganisms which alter the microflora of the host and exert beneficial health effects by improving the microbial balance of the gut[5,6], if provided in appropriate and regular quantities[48]. Probiotics in a healthy animal stimulate non-specific immune response and enhance the system of the immune protection[49]. The most common probiotics are the yeast *Saccharomyces boulardii* and the bacteria, *Lactobacillus* spp., *Enterococcus* spp., *Pediococcus* spp. and *Bacillus* spp.[48,49]. Four mechanisms have been reported to explain the protective effects of probiotics: (1) antagonism through the production of antimicrobial substances, (2) competition with the pathogen for adhesion sites or nutritional sources, (3) immunomodulation of the host, and (4) inhibition of the production of bacterial toxins[49]. Another possible mechanism by which a probiotic may exert beneficial effects is through its effect on the permeability of the gut, which may increase nutrient uptake and thus improve growth performance. Unfortunately, research results have failed to consistently demonstrate beneficial effects on growth[6].

Specialized proteins

In livestock nutrition, considerable attention is given to protein products because their amino acid building blocks are a major constituent of the biologically active compounds in the body[50]. In addition to providing amino acids, spray-dried animal plasma and egg products also serve as functional proteins that may provide additional health benefits.

*Animal plasma***:** Dried blood products have been used in the feed industry for many years, and these products are usually considered as quality protein sources[50,51], especially for starter diets in pigs[52]. Spray-dried plasma protein (SDPP) is produced by the separation of whole animal blood into a plasma and cell fractions by centrifugation followed by drying procedures[52]. Spray-dried

plasma protein contains a mixture of functional components consisting of immunoglobulins, albumin, fibrinogen, lipids, growth factors, peptides, enzymes, and other factors that have biological activity independent of their nutritional value[50]. Several modes of action of SDPP have been proposed, but most evidence supports the concept that consumption of SDPP regulates inflammatory responses[50,51,52,53]. Furthermore, SDPP influences intestinal tight junction integrity and barrier function, although the exact mode of action at this level remains unclear[53]. It is well documented that the use of SDPP has consistently improved pig performance[50,51,52,53], especially during the post weaning period[51,52,53]. However, emergent pathogens have limited the use of SDPP due to their potential role in pathogen transmission, although new manufacturing technologies are suggested to improve the biosafety of SDPP[54].

*Egg yolk antibodies***:** Egg yolk antibodies (EYA), generally referred as IgY, are produced by laying hens[55]. Laying hens are injected with specific pathogens, which induce an immune response that results in the production of antibodies[55,56]. The resulting antibodies are typically transferred to the egg yolk, from where they can be extracted and processed[55]. These antibodies can be administered as whole egg powder, whole yolk powder, a water-soluble powder, or purified IgY, directly to the animal or incorporated into diets[56,57]. The exact mechanism through which IgY counteracts pathogen activity have not been determined precisely[57]. However, several mechanisms have been proposed: (1) inhibition of microbial adhesion to cell surfaces, (2) bacterial agglutination with resulting in a reduction in bacterial numbers, (3) improved phagocytosis activity, and (4) toxin neutralization[56,57] with inhibition of adhesion considered the primary action mechanism[56]. Oral administration of IgY appears to have considerable potential as means of controlling enteric and non-enteric diseases from bacterial or viral origin, and

exerting growth promotion activities in multiple species[56,57], although the results of experimental application of these antibodies have not always been consistent[4,55].

Yeast derivatives

The three most widely used yeast-derived products are the yeast cell wall, mannanoligosaccharides (MOS), and β-glucans[58]. The yeast cell wall has been used as a prebiotic and immunomodulator, but their specific modes of action are not fully understood[58]. MOS, commonly referred to as mannans, represent surface polysaccharides that make up 20% of the yeast cell wall and serve to store energy[59]. MOS enhances resistance to enteric disease and promotes growth by: (1) inhibiting colonization of enteric pathogens by blocking binding sites on bacteria, and (2) enhancing immune response by influencing the innate and adaptive immunity[58]. β-glucans are glucose polymers that are major structural components of the cell wall of yeast, fungi, and bacteria, but also of cereals like oat and barley[60]. The effects of β-glucans are highly dependent on the source and structure[61]. The most observed mode of action is the induction of innate and adaptive immune responses such as phagocytosis, oxidative burst and upregulation of cytokines and chemokines which have been suggested to contribute to the increased resistance against infections observed after β-glucan enteral and parenteral interventions[60,61]. Several benefits of the use of yeast derivatives have been proposed, but the benefit for animal immunity remains unclear[58].

Zinc

Zinc is a trace mineral with an essential role in multiple physiological processes[62,63,64]. To meet basal livestock requirements, dietary Zn levels of 50 to 100, 40 to 60, and 30 ppm are enough to meet swine[62], poultry[65], and beef cattle[64] requirements, respectively. However, supplementing Zn

at higher concentrations of 2,000 to 3,000 ppm for nursery pigs[24], 120 to 180 ppm for poultry[65], and 60 ppm for beef cattle[64] is known to further improve performance. Supplemental Zn, fed conventionally as Zn oxide or Zn sulfate[24,64], has been shown to positively impact postweaning growth and feed efficiency in piglets[66,67,68], improve growth performance, carcass traits and meat quality in broilers[13,18], and improve feed efficiency in finishing heifers[64]. The mode of action of Zn is not well understood[24,70]. The main hypotheses include: (1) antimicrobial properties, by binding and disrupting bacterial cell membranes or through bacterial cell toxicity at higher Zn concentrations; (2) regulation of the immune response by reducing the expression of genes involved in inflammatory processes or through cell-mediated immune function; and (3) maintaining normal function of intestinal barrier and integrity[66,70,71,72]. Precaution must be taken while adding Zn to the diets in higher concentrations and for extended period of time due to toxicosis, especially when highly available Zn sources are used[24,63]. For example, high doses of Zn should not exceed 3 weeks after weaning in pigs[24]. In addition, pharmacological use of Zn in nursery pigs could play a role in the selection and persistence of methicillin-resistant *Staphylococcus aureus* (MRSA)[73]. Likewise, pharmacological Zn use for extended periods of time could have negative consequences on copper absorption[63]. Also, it is important to consider that the level of Zn excretion is directly proportional to Zn intake[74].

Vaccines

Vaccination for prevention of infectious diseases has been routinely practiced for decades and has proved to be one of the most cost-effective methods of disease control[75]. The immune system is composed of two functional branches: (1) the humoral immune system, which primarily produces antibodies and (2) the cell-mediated immune system, which primarily involves the activation of phagocytes and antigen-specific responses[2]. The aim of vaccination is to stimulate

the humoral immune system by increasing antibody production with minor disruption of the cellular immune system[43]. To be acceptable to producers, a vaccine along with being effective must have the following traits: inexpensive, stable, adaptable to mass vaccination, and confer a strong and long-lasting immunity with no or minimal adverse side effects in the vaccinated animal[8]. Commonly used veterinary vaccine technologies are generally classified into live-attenuated and inactivated/killed vaccines[2], among others[75]. Live attenuated vaccines have a strong immune response, induction of cell-mediated and humoral immunity but with lower safety profile and risk of reverting to full virulence. Inactivated vaccines are safe to use and inexpensive to produce but induce only humoral immune responses and require adjuvants[2,43,75].

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